

MATERIALS TESTING

GILKEY • MURPHY • BERGMAN

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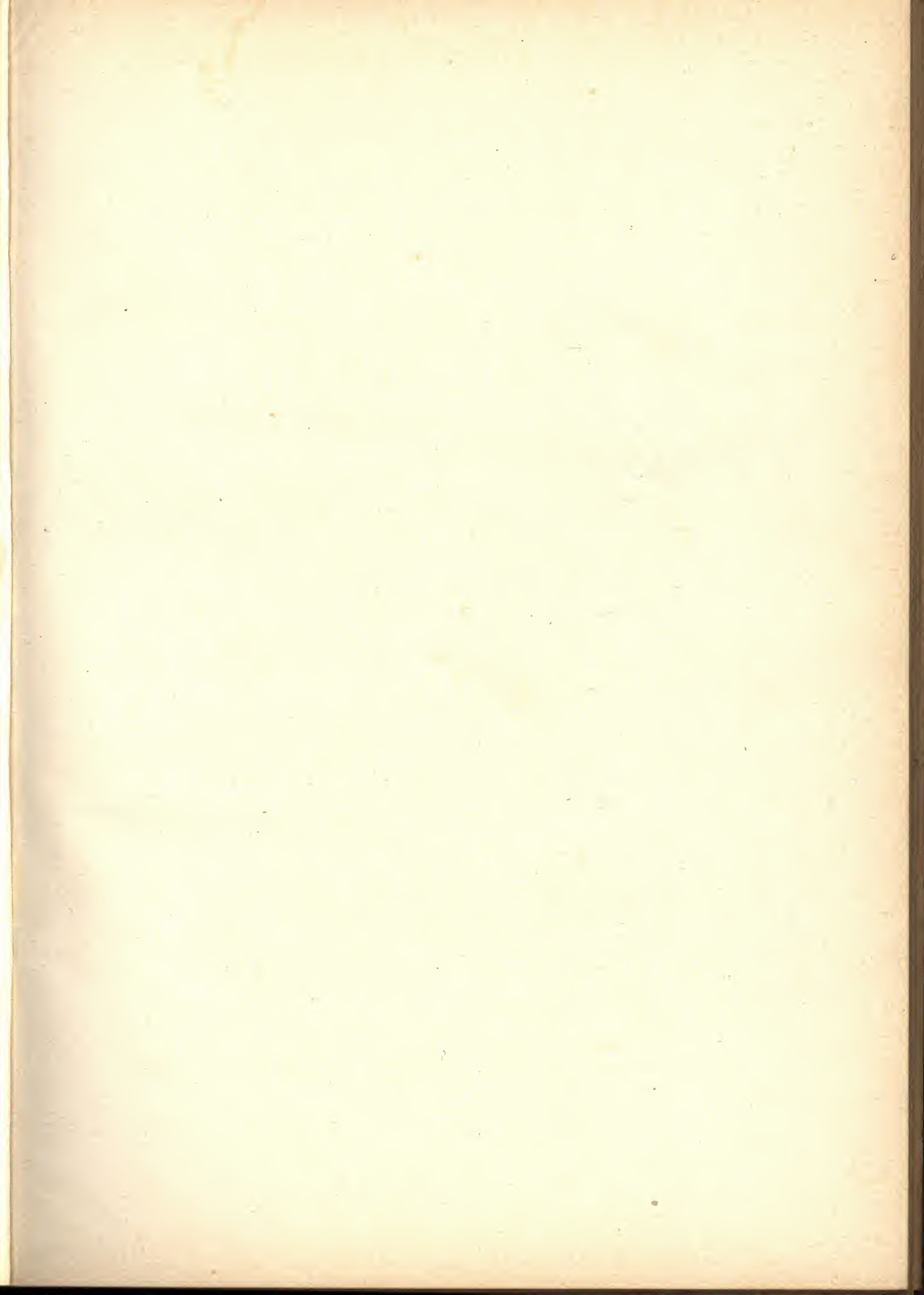


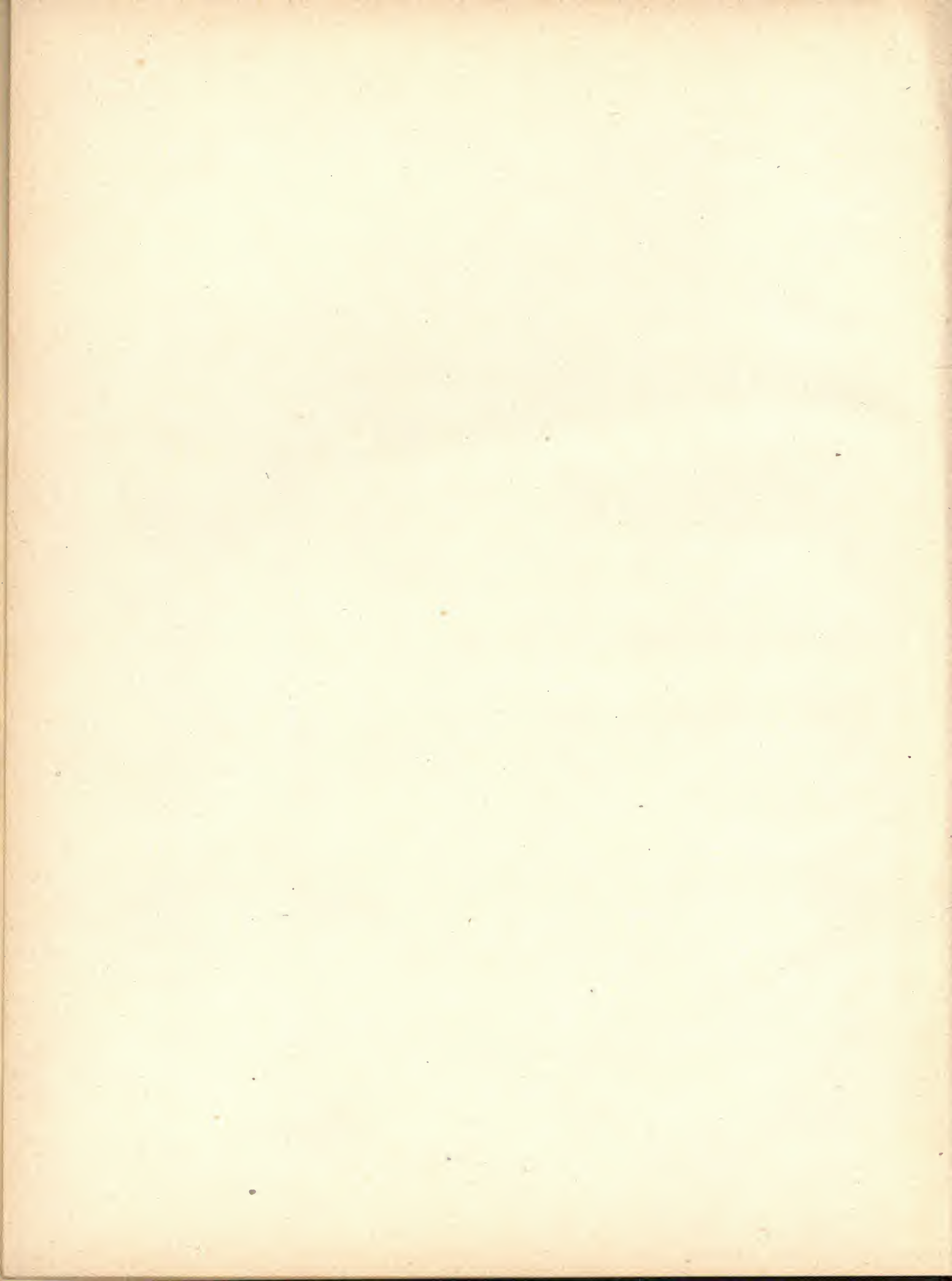
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MATERIALS TESTING

*The quality of the materials used in the manufacture
of this book is governed by continued postwar shortages*

MATERIALS TESTING

*Theory, Practice and Significance of Physical Tests
on Engineering Materials*

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MATERIALS TESTING

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PREFACE

Far from being a mere appendage to the mechanics of materials, to which status it has too often been relegated, materials testing can be and should be made one of the most significant and broadening (in a technical sense) of the courses in any engineering curriculum. The course offers a rare opportunity for the student to get a preview of real engineering, "the art and the science of controlling the forces and the materials of nature and adapting them to the needs of man," for here he is dealing firsthand with those forces and those materials with which the engineer must always concern himself.

To measure up to its possibilities, the work must be *taught* to a much greater extent than has usually been done, for in a different setting even the better students often fail to recognize much of the material to which they have elsewhere been well exposed. The work of the laboratory needs constantly to be tied up with and related to that of the classroom. This manual is the result of evolutionary processes extending over nearly twenty years, being the outgrowth of a long-standing desire to produce a book that harmonizes with the following concept of materials testing and its function in the education of engineers.

The well-rounded course in materials testing is one of multiple objectives. To an anatomy of derived formulas and tabulated properties, it should supply the flesh and blood of reality. It should be made the proving ground whereon these formulas and properties lose their sacredness and their mystery and are recognized for what they are—useful, but not infallible, tools of engineering.

Although the student must be trained in the operation of testing equipment, in the taking of data, and in the preparation of reasonably neat reports, mere interest and proficiency in manipulative operations must not be accepted as the primary objective or as a criterion of mastery. Major emphasis should always be focused upon an understanding of the purposes of the test and the significance of the data secured. The student should be given an insight into the function and background of purchase specifications and into the need for and methods of inspection and the making and interpretation of acceptance tests.

He should learn the distinctions between and the reasons for functional differences in the following:

1. Tests which are made primarily
 - a. For purposes of illustration, verification, and correlation with the mechanics of materials (academic and demonstration tests).
 - b. As a basis for acceptance or rejection of materials (acceptance tests).
 - c. To evaluate fundamental properties; as a basis for design or purchase specifications (research tests).
 - d. As an aid to design (usually some form of model test).
2. Specifications which are evolved
 - a. As a basis for design.
 - b. As a basis for purchase of materials.

Although relatively few engineering graduates expect to become testing engineers, most of them must at times plan and specify tests and interpret the results from tests. To that end it is essential that every engineer be familiar with the nature and scope of the A.S.T.M. and related specification-making bodies whose activities are all or largely in the field of materials.

The testing of materials is constantly assuming a more important role in engineering, which places upon the engineering college increasing opportunities and obligations in this field. The student needs motivation as well as grounding, for subsequent to graduation he will probably find it necessary to supplement his knowledge of materials steadily to keep pace with the developments in the field and the requirements of his position. It is important, therefore, that he be made to realize that in college he is receiving only an introduction to materials testing rather than completing it. This means that the work should be taught suggestively with the emphasis upon possible extensions rather than with the finality that implies coverage.

The foregoing discussion formulates by implication a formidable group of objectives which, like most objectives, may be approached rather than attained. It is to progress toward these objectives that this book is dedicated.

With few exceptions the teaching of materials testing has been from notes prepared locally, to conform to the available equipment, and has been designed to incorporate and emphasize the aspects of the work which the instructor deemed most important or in which his interest happened to be greatest. There has been a valid question as to whether or not a textbook could be made sufficiently inclusive to meet the varied needs of different laboratories both as regards equipment, course content, and emphasis. The decision finally reached by the authors was affirmative. This manual purposely includes more material than any single laboratory is likely to be able to use, but it is hoped that each interested laboratory can find in usable form all the material deemed essential to meet its requirements. It is hoped, moreover, that any instructor will be able, within the scope of this presentation, to find the basis for according emphasis as he desires and, in addition, that the rather broad outlook may prove constructively suggestive as to what to emphasize.

The introduction of chapter material constitutes an attempt, not only to supply the student with guidance and perspective, but also to meet the expressed need for more teaching of the subject in order to build up background for the tests, to raise and answer questions of why, and to breathe significance and purposefulness into specified operations.

Much supplementary material not sufficiently relevant for inclusion in the chapters or the formal problems has been introduced by the "straw-man route." All manner of questions are appended, most of them being designed to direct attention to specific items that are discussed under the guise of "answers." Among the "straw-man questions" many items of interest to testing engineers and technicians as well as to younger instructors and recent graduates are included. Some questions are of the usual checkup or accountability type, relating solely to matters fully covered in the text.

Chapter XII on Experimental Aids in Stress Analysis outlines some of the rapidly developing supplementary aids to stress analysis. Here attention is directed to the effects of localized conditions, a topic of great practical importance but one scarcely touched upon in the formal courses to

which the student has been exposed. The purpose is to supply a brief but graphic preview of complicating realities and to provide just a glimpse of some of the tools that are becoming increasingly useful in the field of engineering design.

While the normal scope of materials testing is undergraduate, much of the supplementary material of this book makes an excellent nucleus around which graduate study and thesis work can be developed. Although this will usually be at the master's level, it need not necessarily be so restricted.

Chapter XI is supplied for the use of institutions that depend upon the work in materials testing to cover their offering in plain concrete. The text treatment is parallel to Chap. II in that it summarizes the basic concepts and definitions that are prerequisite to an understanding of the problem.

The index is unusually complete in order that any topic touched upon even lightly, whether in text, problems or questions, may be made immediately accessible.

In the accompanying Foreword to Instructors the authors discuss specific points likely to be of interest to those contemplating the possible use of the book.

It is inevitable that the authors should be indebted to a great many current and former coworkers, for this book represents the results of a twenty-year incubation period at three major institutions, the University of Illinois, University of Colorado, and Iowa State College. Without attempting to enumerate their creditors by name, lest there be oversight or unbalance, the authors wish nevertheless to record their indebtedness to persons at all three of these institutions for stimulus and suggestions, much of which was doubtless given unconsciously.

More recently the authors have become greatly indebted to Professor H. F. Moore of the University of Illinois for a critical and most helpful review of the present manuscript in its preliminary form. They are also indebted to Professor George C. Ernst of the University of Maryland. To Miss Bernice Bruce the authors are indebted for the invaluable assistance that only an alert, interested, and remarkably competent secretary can supply.

Several manufacturers of testing equipment supplied illustrations which are acknowledged in the body of the book.

AMES, IOWA,
August, 1941.

H. J. GILKEY,
GLENN MURPHY,
E. O. BERGMAN.

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FOREWORD TO INSTRUCTORS

Instructors teaching from the manual for the first time may find it helpful to know something of how the work in materials testing is organized and taught at the school where the present edition originated.

At Iowa State College the work in materials testing laboratory is required of all engineering students, being scheduled for the junior year. Civil, chemical, and ceramic engineering students take the work for two term credits which calls for two 3-hr. contacts per week for one term of 3 months (about 10 weeks of classwork). Students in the other engineering curricula take the work for one term credit, having one 3-hr. contact per week for about 10 weeks. In a school operating under the semester system, the time available for one semester credit would be about midway between these two courses.¹

Problems 1 to 14 with the corresponding text material of Chaps. I to IX are normally included in the two-credit course, while Probs. 4 to 9, 11, and 13 are included in the one-credit course. Students in the two-credit course are required to have the current edition of "Selected A.S.T.M. Standards for Students in Engineering," which is studied and used in conjunction with certain of the tests as if the standards were purchase specifications, with a view to developing an understanding of the nature, origin, and enforcement of specifications for engineering materials. In general, two recitation sessions are devoted to a consideration of specifications in addition to the incidental use of the specifications and methods of test in performing the experiments and preparing reports. Toward the end of the quarter a written report on an outside study of some special phase of materials testing is required of each

student in the two-credit course. A final demonstration lecture on the material of Chap. XII is included for all the students in both the one- and two-credit course, one question of the final examination being devoted to some feature of the material covered by the lecture.²

It has been found desirable to start the course with an experiment of the demonstration type in which the instructor explains and illustrates manipulative operations and has the entire class record data, from which each student prepares an individual report. Problem 4 has been found to be well adapted to this use. While this is the only illustrative test ordinarily conducted at Iowa State College, instructors at some institutions make greater use of this method as a means of handling more students with limited facilities. Where the demonstration method is used, there is an advantage in some experiments (such as those in beams or columns) in employing full-size members instead of the relatively smaller specimens ordinarily used by individual squads. Almost any of the tests can be adapted to the demonstration method. In their experience the authors have found that the demonstration method can easily be overdone since most of the students obtain from such tests interesting glimmerings rather than technical mastery.

Chapter X and Probs. 15 to 17 are also considered to be of first line importance, and one or all of them may well be added or else substituted for some of the other problems, if suitable testing equipment is available, or Chap. X may be assigned without performing Prob. 15, 16, or 17. Problem 2, 3, 7, or 9 would probably best be omitted if a substitution is desired.

Occasionally the work in materials testing includes all the work that is offered on plain concrete. Chapter XI is to meet such a need and would normally be omitted by those schools which

¹ At Iowa State College the two-credit course has been much more satisfactory than the one-credit course. The additional contacts and greater scope of material covered promote student interest. The contrast is so pronounced that the present plan is to abolish the one-credit offering in favor of the two as fast as the shift can be arranged. The material is so arranged that the instructor may readily adapt the course which he outlines to the time which the curricula have allocated to it.

² An evening period has usually been substituted for one of the last scheduled laboratory sessions in order that a single demonstration lecture be made to suffice for several sections.

allot a special course to that important topic. In spite of its apparent length Chap. XI is highly condensed and contains material, much of which differs materially from anything available elsewhere. The language of concrete is a varied one and many of those most expert with certain of its aspects are quite ignorant of others. Chapter XI and the two subsequent problems (18 and 19) are covered in a manner designed to break down the nomenclatural barriers that have existed between the laboratory and the field. For example, the field man accustomed to thinking of the water-cement ratio in terms of gallons per bag may be confused by the laboratory technician's expression of the ratio by absolute or solid volumes or by weight. The proportions of the other constituents are subject to the same more or less confusing multiplicity of units. It has been the aim to express all terms, quantities, and relationships in different current units; to reduce both the practical and analytical aspects of concrete to a common denominator with fully illustrated cross conversions. Figure 20 and Table V might be said to cover the language of water-cement ratio; Fig. 26 with its extensive illustrative tabulation covers the extreme ranges for concrete mixtures from materials of a given grading, while Fig. 27 with its extensive tabulation illustrates the range of mixture obtainable from graded aggregate of the greatest possible size range.

Throughout most of the book illustrative data sheets have been omitted intentionally because the authors feel that in planning a data-sheet layout the student is required to think the problem through much more thoroughly than he is likely to do if supplied with blank spaces to be filled in as he secures his data. An exception to this practice has been made in Probs. 18 and 19, for which illustrative data sheets are supplied. Sample data sheets are shown in detail in an attempt to insure the inclusion of all the essential data covering whatever phases of the problem the instructor elects to emphasize.

Even if the testing of the concrete specimens is combined with Prob. 6 (the compressive test), a minimum of two or three periods will be required for that portion of the work.

While the treatment of concrete is not prepared primarily to be used as a basis for a separate course in plain concrete, it can easily be expanded to serve that function. Such an expansion would require the use of some of the supplementary references

listed after Chap. XI and should also include some of the additional tests outlined in the A.S.T.M. Standards. Some instructors are likely not to be interested in so complete a coverage of the concrete field as has been attempted, especially as regards the data indicated on the illustrative data sheets of Probs. 18 and 19. In such cases the instructor should delimit the problem and designate to the class the data that are to be secured.

The questions given after chapter and problem presentations and discussed in the Appendix are greatly in excess of what can be used within the scope of any known course in materials testing. Generally speaking, the instructor will wish to select carefully, from among the many, a few questions covering the aspects of the work that he particularly wishes to emphasize. They may be definitely assigned as supplementary text material with sufficient time borrowed from the laboratory period for class discussion. Care needs to be exercised to avoid overassignments by expecting more of students than the credit allotted to the course warrants. The authors believe that undergraduate assignments should be restricted to material which can be followed up and upon which there can be placed definite accountability. This does not mean, however, that students, especially the abler ones, should be discouraged from attempting to extend their own purely voluntary studies beyond the range of class assignments. Many of the questions are intended to be motivational, to arouse the curiosity, and to develop the interest of the more alert.

The authors do not consider written discussions of questions desirable, since the tendency is to pad the report without necessarily insuring mastery thereby. The functions that the several types of questions are intended to serve are discussed in the Preface.

Material relating to laboratory organization and conduct of the work given in Appendix B may be modified to suit the needs of the individual laboratory and instructor. In spite of their great effect upon the extent of mastery attained, the details of handling the work have little or no direct bearing upon the scope and objectives set for the course.

The authors always give a final examination in the course, illustrative finals being included as Appendix D. Again this is a phase that may be varied to taste. Final examination questions are intended to emphasize mental rather than manual

aspects and to test the student's understanding of what he has done, and why, rather than simply his ability to explain manipulations.

The authors hope that they have evolved a book that is susceptible of use so varied that differences in equipment and desired emphasis need not be

disturbing. They realize that no book can remove the need for sound, vigorous, and inspiring teaching, but they do hope that this text will promote rather than hinder that type of handling. They welcome constructive criticism, especially from those whose observations are based on actual use.

H. J. GILKEY,
GLENN MURPHY,
E. O. BERGMAN.



MATERIALS TESTING

CHAPTER I

TESTING, TESTING EQUIPMENT, AND TESTING OBSERVATIONS

INTRODUCTION

1. Purposes of the Course.—As a basic course in an engineering curriculum, materials laboratory is intended to

a. Supplement the work in mechanics of materials by illustrating its principles, by verifying representative constants, and by promoting familiarity with leading materials under conditions approximating those of engineering use;

b. Provide some training in the testing of materials, including the use of testing equipment, and the taking, interpretation, and presentation of data;

c. Promote an understanding of the functions of testing, both for acceptance and for research purposes, and to furnish an insight into the nature, purpose, origin, and application of specifications for materials.

2. Importance of Tests.—Since the mechanical properties of materials can be determined only by means of tests and since the proper use of materials depends upon an accurate knowledge of those properties, the importance of correct methods of testing cannot be overemphasized.

3. Standards and Methods of Test.—Experience shows that factors which appear to be minor or unrelated to a test may have a pronounced effect upon the results obtained. In order that different persons and laboratories may obtain similar results from tests on materials which are themselves similar, uniform methods of test have been evolved. While these do not always represent the best, or the only correct, methods of test, they do represent an attempt to provide the necessary uniformity of procedure.

Many organizations formulate and publish standards and methods of test for materials related to their fields of activity. The most important of these in the general field of materials is the American Society for Testing Materials

(A.S.T.M.) which has formulated and published more than 500 standards, tentative standards, and methods of test. There is excellent cooperation between the A.S.T.M. and the other standards-making agencies, such as the Society of Automotive Engineers (S.A.E.), and the American Standards Association (A.S.A.).

The A.S.T.M. is composed largely of engineers engaged in the production, use, or study of materials. Its standards are developed by committees composed of a number of men who are experts in their particular fields.

Upon acceptance by the Society, each specification or method of test is published as a tentative standard to elicit criticism and comments of which due cognizance is taken before the committee recommends that the tentative standard be adopted as a standard. Each proposed standard must be favorably voted upon by the members of the Society before it is adopted as a standard. The standards are revised as necessity arises.

Each A.S.T.M. standard is given a code designation, as A15-39, or E9-33T. The initial letter indicates the general class of the standard in accordance with the following system:

- A. Metallic Materials
- B. Non-metallic Materials
- C. Cementitious, Ceramic, Concrete and Masonry Materials
- D. Miscellaneous Materials
- E. Miscellaneous Subjects—Methods of Test

The first number is the serial number of the standard and the following number indicates the date of last revision. The letter "T" denotes a tentative standard. Thus A15-39 refers to Standard 15 concerning metallic materials with last revision in 1939, and E9-33T indicates the

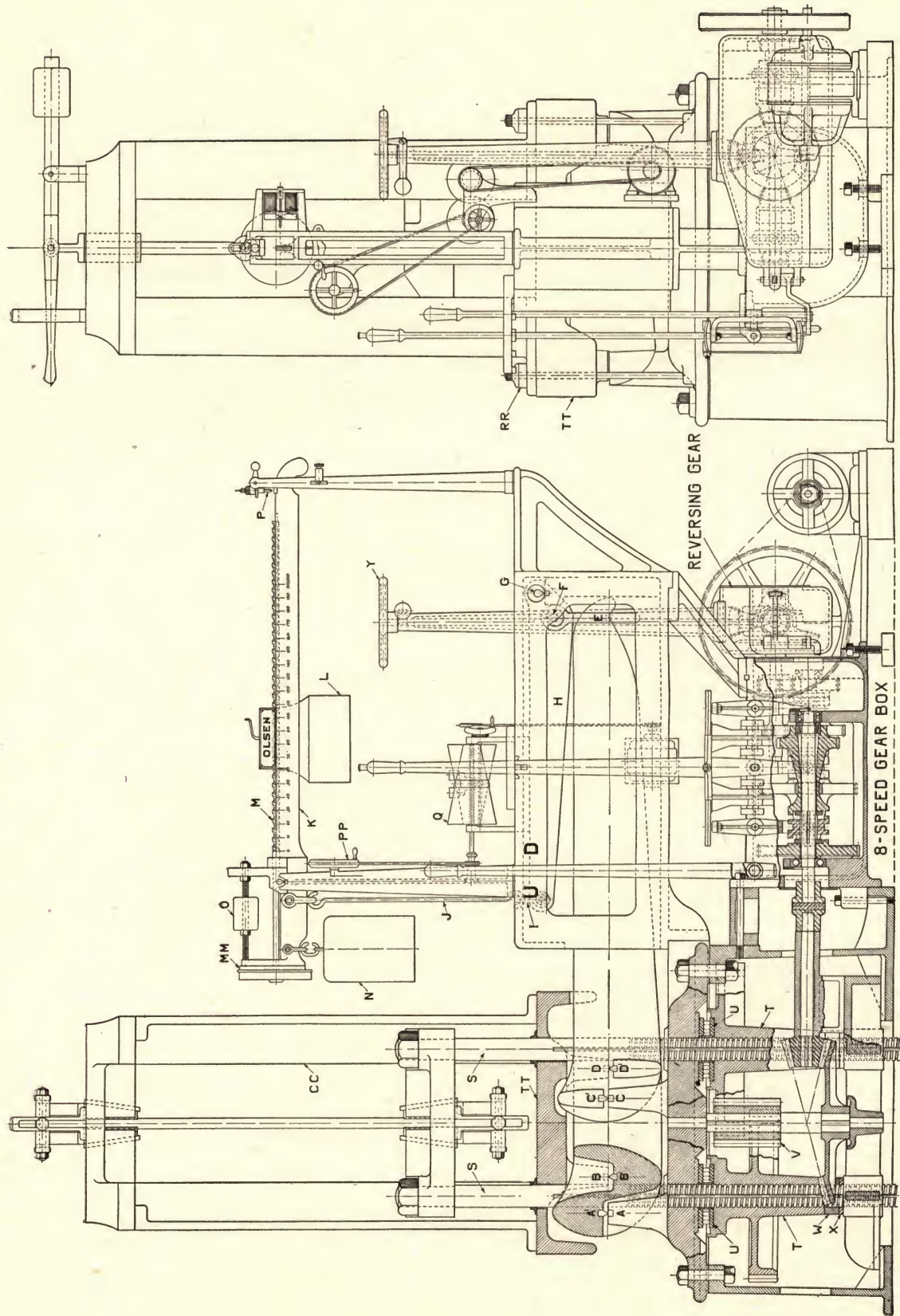


Fig. 1.—Tinus Olsen type. (Courtesy of Tinus Olsen Factory Machine Company.)

$A^1, A, B^1, B, C^1, C, D^1, D$ —Main lever pivots. The levers cast steel. Pivots hardened tool steel; knife-edges are ground to a 90 deg. "V." Pans, or seats are 140 deg. "V"s, excepting those at A and B which are usually flat. This permits slight movement of the main center lever to right or left to prevent cramping. All pivots are designed to carry a maximum pressure of 10,000 lb. per inch of pivot contact length.

E —Main lever and main lever clevis pivot: the main lever is in 3 parts: center, carrying pivots A^1 and B^1 , and two side levers carrying pivots C^1 and D^1 . Center and side levers, of course, have the same multiplication ratio, that is, $\frac{A^1 E}{A^1 B} = \frac{C^1 E}{C^1 D} = 12$ to 18, depending upon capacity of machine.

F and G —Intermediate lever pivot.

H —Intermediate lever: large capacity machine requires more than one intermediate lever.

I —Intermediate lever clevis.

J —Beam Link: the total reduction in the lever system is such that the pull on J varies from a maximum of 100 lb. on a 10,000-lb. machine to 2000 lb. on a 1,000,000-lb. machine. Pull at J for a 100,000-lb. Universal Testing Machine is 500 lb.

K —Beam or steadyard: when the beam is balanced, the position of the poise L indicates the load.

L —Poise.

M —Poise Screw: variations in lead of this screw, due to wear, affect accuracy. Poise hangs on bronze half-nut on screw.

N —Counterweight: balances weight of platen, levers, etc.

O —Counterbalance: An adjustable counterweight to compensate for changes in weight of tools used, grips, etc. This weight can be moved vertically to raise center of gravity of beam-poise assembly to increase sensitivity.

P —Electrical contact for operating automatic poise control.

Q —Variable speed cones for electric-beam drive for advancing the poise at different speeds depending upon desired rate of loading.

PP —Hand poise control.

TT —Platen or weighing table: cast iron or steel.

RR —Rubber recoil washers: to absorb energy released when a specimen fractures. The nuts are screwed down only enough to bring them barely in contact with the washers when machine is unloaded.

MM —Vernier dial: for close reading of load. There are 200 divisions on this dial, the lead of the screw being such that each dial division is $2\frac{1}{2}$ lb. on a 10,000-lb. Universal Testing Machine, 10 lb. on a 100,000-lb. Universal Testing Machine.

CC —Tension-test columns transmit load to weighing table.

S —Pulling screws: these screws do not rotate in the typical Olsen machine but have keyways as shown with keys in the drum cover and the cross casting at the bottom. It is in this way possible to house all rotating parts in the base, to use longer pulling nuts with better lubrication than if they were in the pulling heads, as in rotating screw Universal Testing Machines. Also less "wobble" to screws and pulling heads. Disadvantage: screws project below floor level in long specimen machines.

T —Rotating gear nuts.

U —Roller thrust bearing.

V and W —Gear train to nuts.

X —Wedges for adjusting end play of rotating nuts.

(Courtesy of Tinius Olsen Testing Machine Company.)

1933 edition of Tentative Standard 9 dealing with methods of test.

Complete compilations of the A.S.T.M. Standards are published triennially (1936, 1939, 1942 etc.). Before 1939 they were published in two volumes (Part I, Metals, and Part II, Non-metallic Materials), but the 1939 edition contains three volumes (Part I, Metals; Part II, Non-metallic Materials, Constructional; and Part III, Non-metallic Materials, General). Part II contains standards dealing with cement, concrete, timber, masonry units, road materials, paint, soils, etc.; while Part III includes coal, petroleum products, electrical insulating materials, rubber, textiles, paper, plastics, etc. Each part contains the appropriate standards on general testing methods. Standards are brought up to date annually with supplements published in the intervening years.

Formerly the Standards and Tentative Standards were issued separately, but now each part contains both the Standards and the Tentative Standards that fall within the scope indicated above.

If any question arises regarding the basis for specific clauses which appear in the Standards, information may be secured by writing to the Secretary or to the Chairman of the Sponsoring Committee named in the footnote at the beginning of each Standard. A letter to the Secretary of the A.S.T.M. (260 South Broad Street, Philadelphia, Pa.) would certainly be referred to the proper person. The complete membership of committees is listed in the *A.S.T.M. Yearbook* which is issued annually.

The annual *Proceedings* of the Society contain many original research data in the field of materials, in addition to committee reports and discussions of the published papers. Some of this material has a fairly direct bearing on the evolution of the standards and methods of test, but much of it has no visible connection with standardizing activities, simply adding to the backlog of basic information that must be accumulated before intelligent standardization is possible. The A.S.T.M. is one of the most active of the many agencies which are functioning continuously to advance the knowledge of materials. The *A.S.T.M. Bulletin*, published six times a year, also includes some research reports. The *Proceedings* and the *Bulletin* are distributed to members of the Society and are available in most public libraries.

THE TESTING MACHINE

4. Description.—Some type of a testing machine is used in virtually every systematic test performed to evaluate properties of materials. In addition to primary tests in tension, compression, flexure, and torsion there are various special tests such as those for hardness, impact, and fatigue. In general, special-purpose equipment is needed for each type of test except tension, compression, and flexure for which the so-called *Universal testing machines* are often used.

The Universal testing machine, and others which perform one or more of its functions, are of many types, all of them consisting essentially of two parts: (1) the straining mechanism, and (2) the load-weighing mechanism. With suitable arrangements of gripping or bearing devices, the specimen to be tested is interposed between a fixed head and a movable head. The specimen is strained by controlling the motion of the movable head. The measurement or weighing of the load on the specimen is accomplished by means of lever systems, by pressure cells, or by other devices through which the straining load or some known portion of it must pass.

Figure 1 shows a diagram of a Universal machine in which the movable head is actuated by a gear and screw system. The load is weighed by levers and a scale beam on which is mounted a movable poise. Figure 2 shows a diagram of a Universal machine in which the head is moved hydraulically and the load is indicated by an hydraulic gage. Figures 3, 4, and 5 show diagrams of other representative Universal testing machines.

In Fig. 1 a tension specimen is shown in place, held in the upper head and in the lower or movable head by means of wedge grips. In operation the moving head travels downward, stretching the specimen. The resistance of the specimen develops a downward pull on the upper head. The downward pull is transmitted through the standards *CC* to the platen *TT*. The platen is supported at *B* and *D* on levers *A'B'E* and *C'D'E* forming the platform of a large platform scale. Both levers are connected through an additional reducing lever *H* and a link *J* to the scale beam *K* on which is mounted the poise *L*. As the specimen develops load, the poise must be moved outward to keep the beam in balance, and the total load developed may be read directly on the beam. If a compressive test is being conducted, the specimen is placed

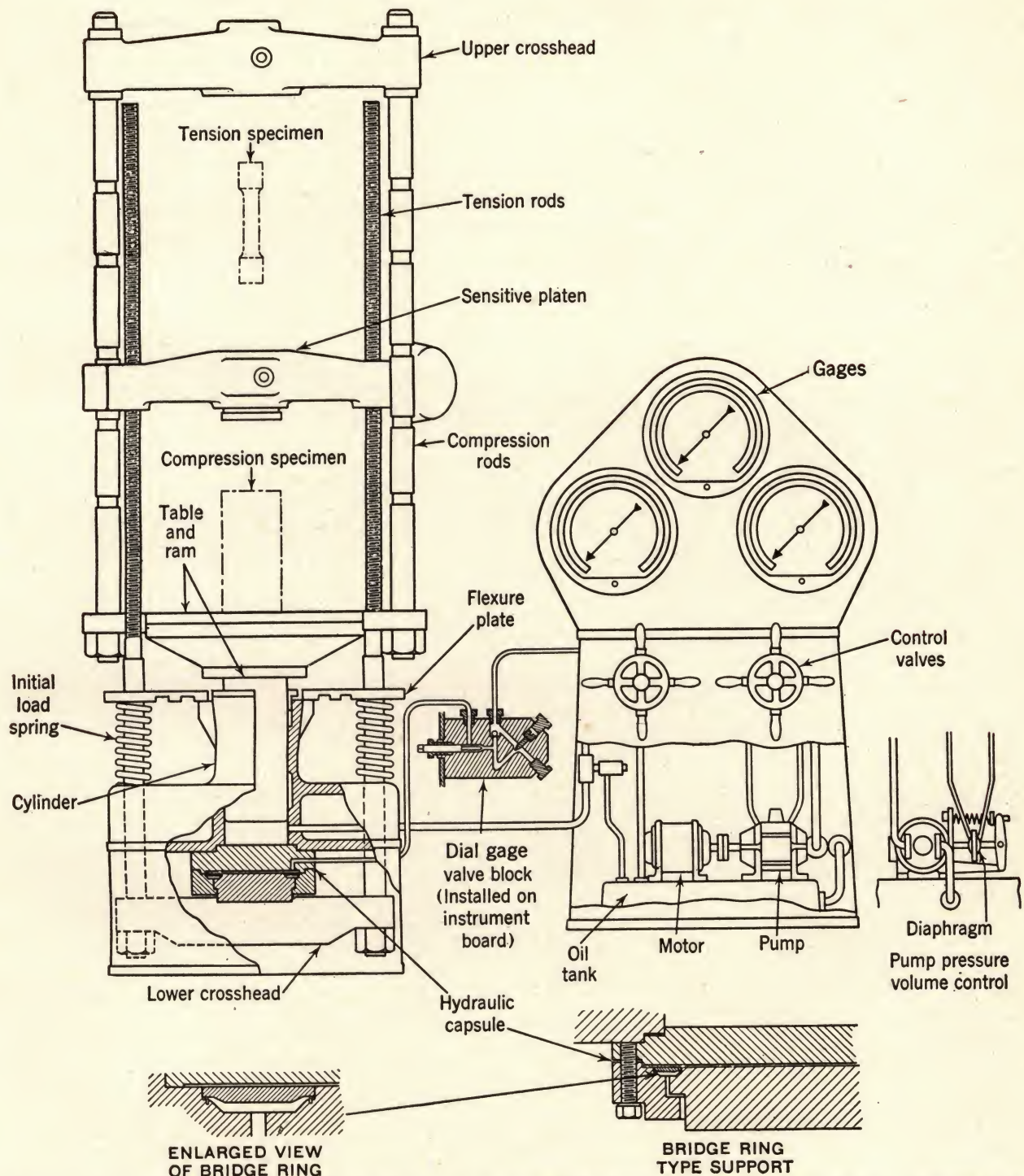


FIG. 2.—Diagram of a Universal hydraulic testing machine equipped with an hydraulic capsule weighing device. (Courtesy of the Baldwin-Southwark Corporation.)

directly on the platen, and the moving head traveling downward, as before, compresses the specimen. In a flexural test the beam is supported

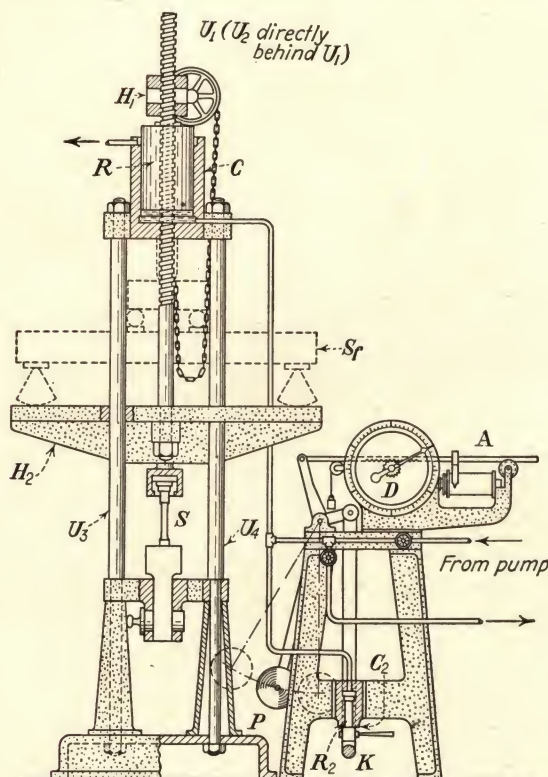


FIG. 3.—Diagram of an Amsler hydraulic testing machine.

on the platen, and the moving head travels downward as in the preceding cases. Note that the moving head travels in but one direction to apply load, regardless of whether the test is compressive, tensile, or flexural.

The screw-gear machine with a lever-type weighing system has been widely used in the past. In recent years, however, the trend, particularly in the larger sizes,¹ has been toward the more convenient hydraulic machines with their wide range of speeds and direct-indicating load-weighting systems.

In the Universal hydraulic machine, shown in Fig. 2, oil is pumped from the supply tank through a control valve into the cylinder. The piston in the top of the cylinder is thereby forced upward, lifting the table, or bottom platen. The upper

¹ The largest testing machine in the world, designed for compression only, is now located at the National Bureau of Standards in Washington, D. C. It is hydraulically operated and has a capacity of 10,000,000 lb. It was built in 1910.

crosshead, which is bolted to the table by means of the compression rods, is also lifted. The upper (sensitive) platen, which is threaded onto the screws may be raised or lowered by means of rotating nuts (not visible) to accommodate specimens of different lengths. The platen remains stationary during a test since the screws pass loosely through the table and are attached to the lower (fixed) crosshead.

Any resistance developed by the specimen as it is strained will increase the pressure of the oil in the cylinder, and the total load developed could be measured by means of a pressure gage attached directly to the cylinder. While this means is used on some of the less costly machines, it is not very satisfactory because of some undesirable features such as the friction between the piston and the cylinder and the possibility of getting air into the gage. In the machine diagramed in Fig. 2, the load is measured by an hydraulic capsule inserted between the main cylinder and the lower crosshead. The gages are attached to the capsule forming a closed system which is filled with oil. Since the system is closed, there is less possibility of air getting into the gages than in the simpler type of weighing system. As a specimen is strained, the load which it develops is transmitted from the fixed head to the lower crosshead by means of the screws which are in tension. The load is also transmitted downward through the platen to the main cylinder in compression, thus subjecting the capsule to compression. The increase in pressure is indicated by the gages, which are calibrated in terms of total load. The machine shown in Fig. 2 has a low-range, a medium-range, and a high-range gage to afford greater accuracy of reading. Other models are equipped with a single dial, having two or more scales, with one scale calibrated for low loads and another for high loads. The magnification can be changed to agree with a change of scale without interrupting the test.

Hydraulic Universal testing machines, produced by other manufacturers, have the same general type of strain-applying mechanism, but somewhat different load-indicating mechanisms. Another example of an hydraulic machine is the Amsler Universal, shown in Fig. 3.

In general, machines that utilize the screw-gear arrangement for producing strain are equipped with the lever-type weighing system, and hydraulic machines have the hydraulic weighing system, but

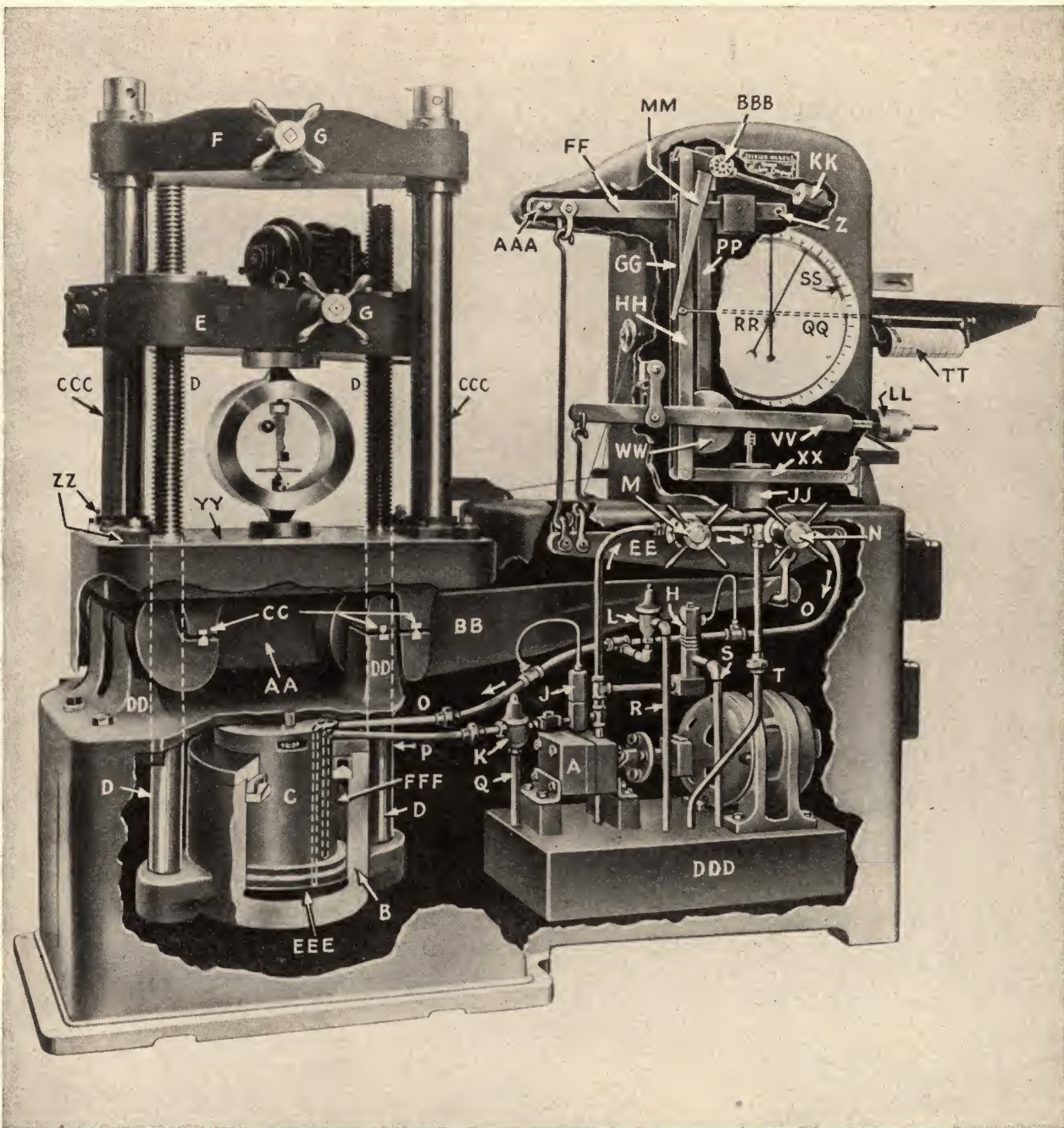
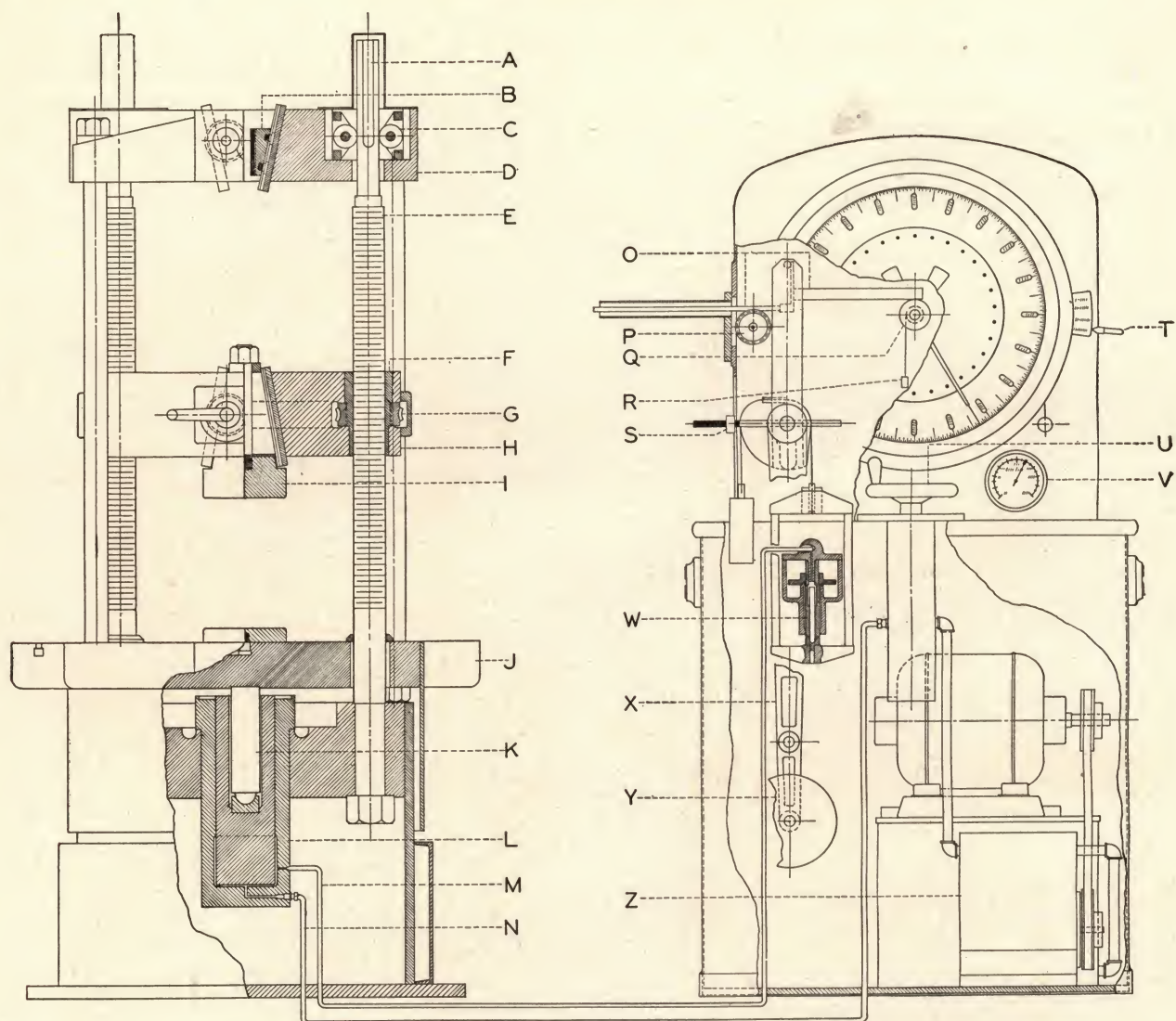


FIG. 4.—Diagram of an hydraulic testing machine with a pendulum-type weighing system. (Courtesy of Tinius Olsen Testing Machine Company.)

- | | | |
|--|---------------------------------|------------------------------|
| A—Oil pump | R—High-pressure relief line | PP—Pendulum arm |
| B—Cylinder casing | S—By-pass return to reservoir | QQ—Pointer pinion rack |
| C—Cylinder | T—Pressure relief to reservoir | RR—Pointers |
| D—Pulling screws | Z—Low-capacity fulcrum seat | SS—Dial |
| E—Lower or movable crosshead | | TT—Recorder drum |
| F—Upper or weighing crosshead | AA—Main center lever | VV—Counter balance lever |
| G—Mechanism for adjusting wedge grips | BB—Main side lever | WW—Pendulum |
| H—Automatic by-pass valve | CC—Hardened pivots | XX—Dash pot links |
| J—Transfer needle valve | DD—Lever stools | YY—Platen |
| K—Low-pressure relief valve | EE—Intermediate lever | ZZ—Recoil shock absorbers |
| L—Overload relief valve | FF—Shift-fulcrum lever | |
| M—Valve for controlling rate of loading | GG—Pendulum compression tube | AAA—Shiftable fulcrum |
| N—Unloading valve | HH—Pendulum pulling straps | BBB—Ball bearings |
| O—High-pressure supply line | JJ—Dash pot | CCC—Tension columns |
| P—Low-pressure supply line to returning cylinder | KK—Pendulum tare weight | DDD—Oil reservoir |
| Q—Low-pressure relief line | LL—Lever counter balance weight | EEE—Main cylinder space |
| | MM—Tangent converter | FFF—Returning cylinder space |

A proving ring is shown in place between the platen and the movable crosshead of the machine.



LOADING UNIT

PENDULUM INDICATING AND PUMPING UNIT

FIG. 5a.—Riehle 60,000-lb. capacity precision hydraulic Universal testing machine (model P2). Typical of machines covering a capacity range from 10,000 lb. to 300,000 lb. (Courtesy of American Machine and Metals Inc., Riehle Testing Machine Division.)

- (A) Upper guide rollers
- (B) Wedge grips
- (C) Upper roller-bearing guide
- (D) Upper pulling head
- (E) Non-rotating screw columns
- (F) Bronze nuts rotated by individual motor drive for adjusting purposes of lower pulling head.
- (G) Worm gear
- (H) Lower pulling head
- (I) Solid compression tool
- (J) Compression and transverse table
- (K) Spherical connection to center of plunger
- (L) Floating packless ram
- (M) Oil line leading to measuring cylinder
- (N) Supply line leading to orifice control

- (O) Indicator rack
- (P) Indicator rack supporting roller
- (Q) Pointer pinion
- (R) Counterweight to eliminate backlash
- (S) Zero adjustment
- (T) Scale range selector
- (U) Handwheel for stepless regulation of testing speeds in both directions
- (V) Dial indicating rate of load per minute of pacing disc
- (W) Floating-type measuring cylinder unit transmitting load to pendulum
- (X) Pendulum arm
- (Y) Removable pendulum weight
- (Z) Pumping or power unit

the other combinations are possible and are sometimes used.

In torsion machines the strain is usually applied

Although the lever system actually measures the force in one of the links, the beam is calibrated in terms of torque, which is equal to the reactive

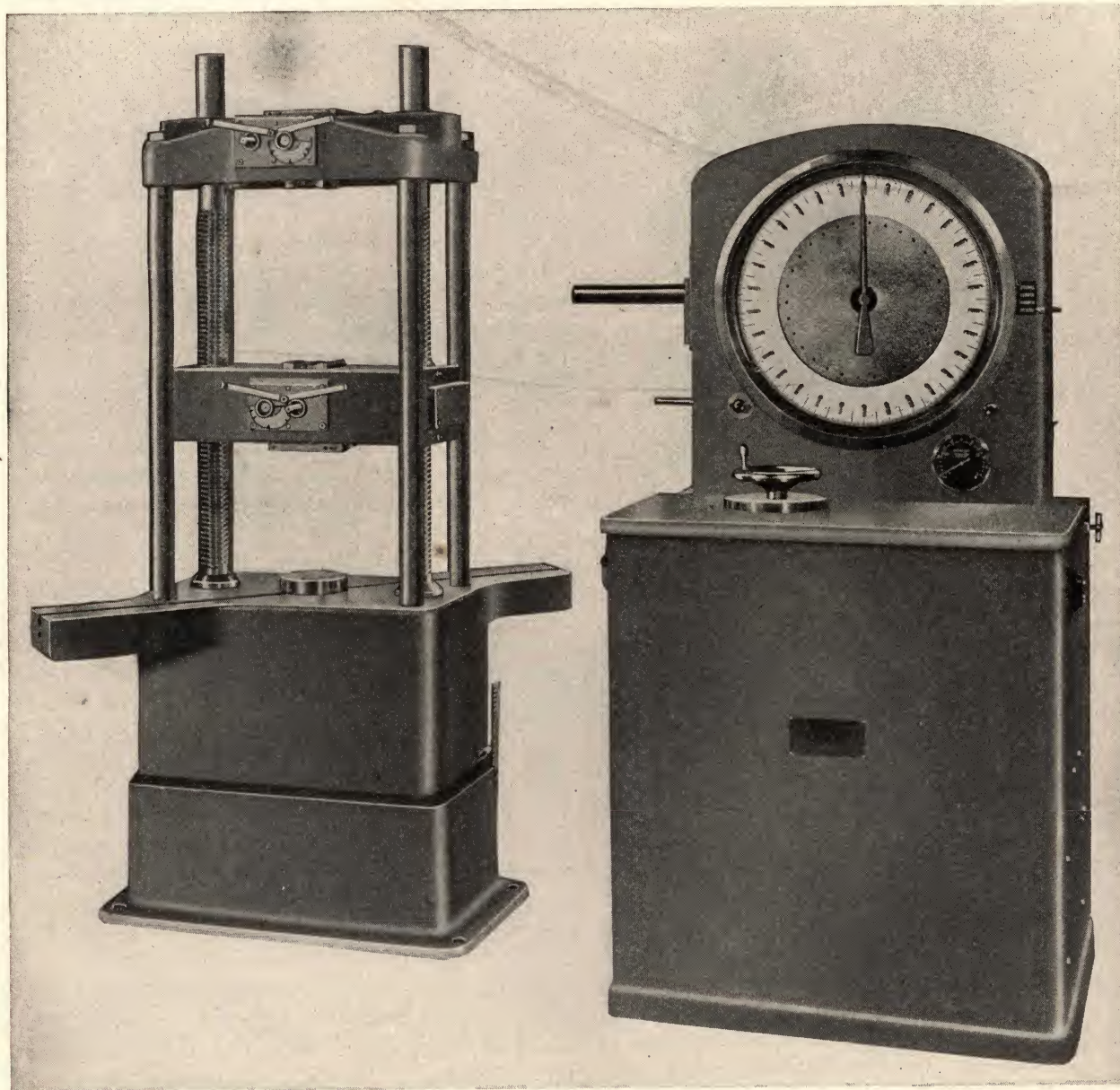


FIG. 5b.—Riehle 60,000-lb. capacity precision hydraulic universal testing machine (model P2). Typical of machines covering a capacity range from 10,000 lb. to 300,000 lb. (Courtesy of American Machine and Metals Inc., Riehle Testing Machine Division.)

by a screw-gear arrangement, but the torque developed may be measured by a lever system, using a scale beam and poise, or by a pendulum. In the former type the torque developed by the specimen tends to rotate the chuck in which the specimen is held. The chuck is prevented from rotating by two links, one of which is attached directly to the frame of the machine and the other, through supplementary levers, to the scale beam.

force against the frame of the machine multiplied by the distance between the two links.

Figure 6 is a photograph of a torsion testing machine with a pendulum-type weighing system. One end of the specimen is twisted by turning the handwheel at the right of the frame. The other end of the specimen is held by a chuck attached to the pendulum at its center of rotation. The torque developed by the elevation of the heavy

pendulum may be noted on a scale across which the arm of the pendulum moves.

5. Development of Testing Machines.—Although

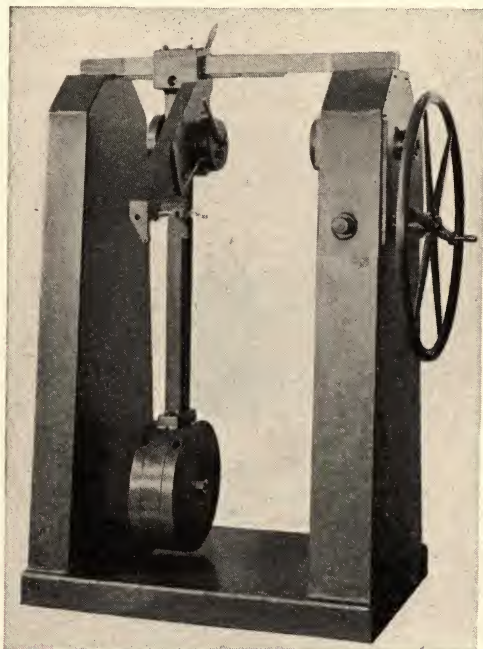


FIG. 6.—Photograph of a pendulum-type torsion machine. (Courtesy of American Machine and Metals, Inc., Riehle Testing Machine Division.)

the Egyptians, or even earlier races, probably experimented with the structural materials which they used, the first tests of which we have a record in this field were conducted about the time the Pilgrims landed in America. Many European testing machines, one of nearly 300,000-lb. capacity, antedated the first machine in America. While the largest capacity machine (10,000,000 lb.) is in this country, a 6,600,000-lb. machine (probably still the second largest in the world) was built in Germany at about the same time. While the record for static-load capacity is of long standing, some of the more recent machines embody features which mark great progress in the testing field. As an essential tool of engineering, the testing machine takes on added importance each year. Data concerning some of the more important testing machines in the United States are tabulated in Table I which was compiled largely from "Materials Testing Machines" by C. H. Gibbons (see references in Art. 8).

6. Definitions.—The more important items relative to testing machines have been indicated and explained in Art. 4 and in Figs. 1-6. A few additional terms warrant definition, however.

a. Multiplication Ratio.—The term multiplication ratio is used in connection with lever-type weighing systems. Since the multiplication ratio of any lever is defined as the ratio of the weight lifted to the lifting force, the multiplication ratio of a lever system of a testing machine is the ratio of the maximum weight which may be supported (the capacity load of the machine) to the balancing force (the weight of the poise). The ratio may be evaluated by measurement of the levers or by weights.

1. RATIO BY MEASUREMENT.—The multiplication ratio of a simple lever is equal to the ratio of the long arm to the short arm and hence may be found by direct measurement. The multiplication ratio for a compound lever system, such as is normally used in a testing machine, is equal to the product of the ratios of the individual levers.

2. RATIO BY WEIGHT.—The multiplication ratio may also be evaluated by dividing the capacity of the machine by the weight of the poise. Any change in the weight of the poise will cause an apparent change in the multiplication ratio. The multiplication ratio by measurement of the levers is not altered by a change in the weight of the poise. It may be considered to be the fundamental multiplication ratio for the machine, since the relationship between the lifted force and the lifting force is not altered. Any change in the weight of the poise will, of course, render the calibrations on the scale beam inaccurate.

b. Equivalent Lever Arm.—This term applies to those torsion machines which employ a lever system to measure the torque on the specimen and may be defined as the length of the lever arm that the poise must have to produce the torque indicated by the machine at capacity load.

In this type of machine the fixed head is attached to a transverse member connected at one end to the frame of the machine and at the other end to the lever system. A free-body diagram of the fixed head will indicate that the torque applied to the head by the specimen must be balanced by a restraining couple acting on the transverse member. One of the forces of this couple is the reaction of the frame of the machine on one end of the transverse member, and the other force is supplied to the opposite end of the same member by the poise acting through a compound lever system. The equivalent arm may be evaluated: (1) by measurement, as the product of the arm of the couple acting on the transverse member and the multiplication

ratio of the lever system; or (2) by weight, by dividing the capacity of the machine by the weight of the poise.

of gravity of the scale beam, but a high degree of sensitivity may make it very difficult to keep the beam in balance during a test.

TABLE I.—SOME OF THE IMPORTANT TESTING MACHINES IN THE UNITED STATES

Date	Capacity, lb.	Kind* of test	Location	Maker	Type: loading (above), weighing (below)	Max. length of specimen (approx.), ft.	Clearance between screws (approx.), ft.	Remarks
1832	21 000+	T	Franklin Institute Museum, Philadelphia, Pa.	.....	Lever 30:1 Dead weight	5.0	1.2	Probably the oldest testing machine now in existence
1866	20 000	T	Conshohocken, Pa.	Riehle	Hydraulic Lever	....	....	Constructed by Banks, Dinmore and Co. (Philadelphia Scale Works). Later became Riehle Company
1871	1 600 000	T	Philadelphia, Pa.	Keystone Bridge Co.	Hydraulic Lever	....	....	Built by James B. Eads for tests in connection with famous Eads Bridge at St. Louis
1879†	1 000 000 800 000	C T	Watertown Arsenal, Watertown, Mass.	Emery	Hydraulic Emery cell	30.0	4.2	Horizontal. Still in service. A famous machine†
1890	2 400 000	T,C,F	Phoenix Iron Works, Phoenixville, Pa.	.....	Hydraulic Bourdon gage	50.0	2.5	
1904	4 000 000	T,C,F	American Bridge Company, Ambridge, Pa.	American Bridge Co.	Hydraulic Bourdon gage			
1910‡	10 000 000	C	National Bureau of Standards, Washington, D. C.	Olsen	Hydraulic Lever—also Bourdon gage	30.0	6.0	Greatest load capacity in the world
1910	2 300 000 1 150 000	C T	National Bureau of Standards, Washington, D. C.	Emery	Hydraulic Emery cell	33.0	4.5	Horizontal
1925±	2 500 000	T,C	John Roebling's Sons, Trenton, N. J.	Riehle	3-screw Lever	25.0	6.3	
1929	3 000 000	T,C	University of Illinois, Urbana, Ill.	Southwark-Emery	Hydraulic Emery cell Bourdon gage	38.5	7.5	First large installation of this type
1931	4 000 000	C	U. S. Bureau of Reclamation, Denver, Col.	Baldwin-Southwark	Hydraulic Emery cell Bourdon gage	7. ±	....	Installed primarily for testing large concrete specimens, Boulder (Hoover) Dam Research
1932	4 000 000 3 000 000	C T,F	University of California, Berkeley, Calif.	Baldwin-Southwark	Hydraulic Emery cell Bourdon gage	33.5	10.0	Extra wide clearances and other original features
1940§	3 000 000	T,C	Aluminum Company of America, New Kensington, Pa.	Baldwin-Southwark	Hydraulic Emery cell Bourdon gage	15.5	7.5	Speed up to 36 in. per min. Great energy capacity§

* C = compression, T = tension, F = flexure.

† Probably the most famous machine in the world. Introduction of the sensitive Emery pressure-cell weighing system was its most important feature. At time of acceptance a horsehair was broken at a measured load of 1 lb. immediately following the breaking of a wrought-iron bar at 722,800 lb.

‡ Originally located at Pittsburgh, Pa. and able to accommodate a specimen about twice as long (about 60 ft.) but was shortened, because of limited headroom in the building, when moved to Washington, D. C., about 1921. Continues (1941) to be the highest capacity testing machine in the world. The Bourdon gages were added a few years ago as auxiliary weighing devices.

§ Named the "Templin Machine." The most powerful, although not the highest capacity, testing machine in the world. Can apply load up to 36 in. per min. which at its rated capacity requires about 273 hp. A 300-hp. motor is used.

c. Sensitivity.—The sensitivity of a testing machine is indicated by the response of the load-weighting system to small changes in load. A sensitive machine is not necessarily an accurate machine, as sensitivity and accuracy are entirely unrelated. The sensitivity of a lever-type weighing system may be increased by raising the center

d. Sluggishness.—Sluggishness is the lack of sensitivity and may be measured as the change in load required to produce an appreciable response² of the beam or other load-indicating mechanism. In the lever-type weighing system sluggishness may be

² Generally taken as $\frac{1}{2}$ -in. vertical movement of the free end of the scale beam for the lever-type weighing system.

due, in addition to a low center of gravity of the scale beam and inertia of the platen and levers, to misplaced, dulled, or dirty knife-edges. Sluggish-

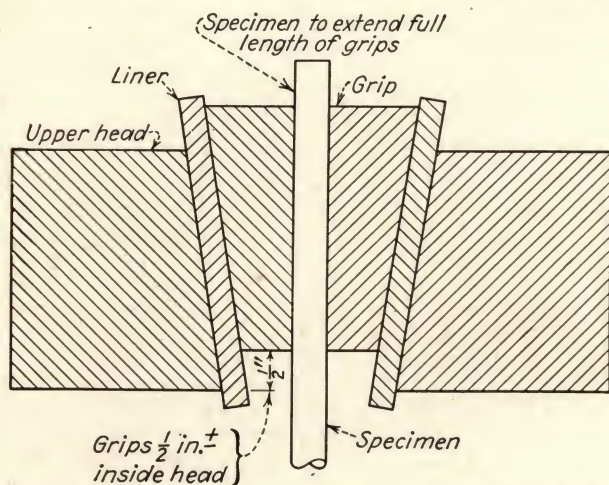


FIG. 7.—Correct placement of tensile specimen in wedge grips.

ness may introduce errors of reading which are just as important as those caused by incorrect weight of the poise, errors in lengths of levers, and in calibration of scale beams or dials. Since the sluggishness of a weighing system does not necessarily increase as the load increases, the percentage error due to sluggishness is usually greatest at low loads.

e. Error.—The error of a weighing system is defined³ as the load indicated by the machine minus the correct load. Error may be positive or negative.

f. Correction.—The correction of a weighing system is defined³ as the correct load minus the indicated load. It is equal in magnitude to error but opposite in sign.

7. Cautions.—To avoid damaging the testing machines, the following rules should be observed:

a. No Unauthorized Use.—No testing equipment should be operated or otherwise handled until it has definitely been assigned for use during the specified period.

b. Have Controls Explained.—Do not operate a testing machine for the first time until the instructor has explained the controls. Most testing machines have individual features that necessitate special handling in one respect or another.

c. Try Out the Machine.—After the above explanation the machine should always be tried out thoroughly before the beginning of the test.

d. Clutches.—When using a machine having two clutches, make sure that both clutches are disengaged before attempting to engage either one.

e. Shifting Gears.—Stop machine or disengage clutch before shifting gears, and then proceed cautiously. Do not attempt to force gears.

f. Never Leave Machine Running.—Never leave the machine or its controls unless the power has been disconnected.

g. Avoid Reversing Motor Suddenly.—If the motor is reversed suddenly while it is running, a fuse may be blown. Always allow the motor to come to a stop before reversing it; that will take less time than replacing a fuse.

h. Slow Speed for Testing.—Use the slowest speed for testing unless definitely instructed otherwise. The highest speed is for use solely in positioning the head of the machine.

i. Balance at Start.—Balance the beam at zero load before beginning a test.

j. Keep Balanced.—Keep the poise at or beyond the point of balance at all times.

k. Clean Grips and Liners.—Liners and the backs of grips for tensile testing should be wiped free of rust, scale, and grease before use. The backs of grips and liners should not be oiled, but they may be coated with tallow to facilitate removal after testing.

l. Support for Grips.—In preparing for a tensile test insert enough liners to bring the thinner ends of the wedge grips about $\frac{1}{2}$ in. back inside the supporting head, as indicated in Fig. 7. This precaution should prevent the grips from being drawn through and projecting beyond the heads as the test progresses.

Appreciable projection beyond the face of the head may result in breakage.

m. Gripping Length.—The specimen should extend the full length of the grips; otherwise slippage of the specimen or breakage of the grips is likely to occur (see Fig. 7).

n. Do Not Strike Grip or Grip Holder.—Grips are very brittle and should never be struck with anything harder than a copper hammer. Never strike a grip holder. If the grips stick, consult the instructor.

o. Avoid Scarring.—At all times suitable precautions should be taken to avoid scarring or scratching the bed, head, or screws of the testing machine. A cast-iron bearing plate should always be placed between a compressive specimen and the bed of the machine. The platens of the older testing machines

³ A.S.T.M. Designation E4-36.

in most laboratories illustrate the need for precautionary measures of this kind.

p. Unusual Sound or Behavior.—Disconnect the power, and consult the instructor promptly in all cases of unusual behavior or sound of motor or machinery.

q. Recoil Nuts.—Do not tighten the recoil nuts. At zero load they should be barely in contact with the recoil pads.

r. Allow for Coasting.—In bringing the head to position, allowance should be made for coasting after the clutch is disengaged. At the high speed this may amount to as much as 1 in.

8. References on Testing Machines.

- a. A.S.T.M. Designations E4-36, E8-40T, E9-33T.
- b. Gibbons, C. H. "Materials Testing Machines," Instruments Publ. Co., Pittsburgh, Pa., 1935. Also published in *Baldwin Locomotives*, Vols. 13-14, April, 1934-July, 1935.
- c. Moore, H. F. "Textbook of the Materials of Engineering," 5th ed., McGraw-Hill Book Company, Inc., Chap. XVIII, 1936.
- d. Withey, M. O., and James Ashton. "Johnson's Materials of Construction," 8th ed., John Wiley & Sons, Inc., New York, 1939. (Also available in earlier editions.)
- e. Catalogues of testing machine manufacturers.
 1. Amsler and Company, Schaffhouse, Switzerland; U. S. agent, Herman A. Holz, New York.
 2. Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
 3. Riehle Testing Machine Division, American Machine and Metals, Inc., East Moline, Ill.
 4. Tinius Olsen Testing Machine Company, Philadelphia, Pa.

INSTRUMENTAL EQUIPMENT

9. Use.—For most routine acceptance tests no special instrumental equipment is needed other than a micrometer, scale, and dividers. However, in testing to determine many of the properties, particularly those within the elastic range of loading, more sensitive instruments are required to measure strains or deflections. A variety of equipment for these purposes is on the market and as a result of much improvising a still greater variety is in use in the laboratories of the country. In research work especially, it is frequently necessary to build special instruments to make the desired measurements. Mention will be made of a few of the more common devices which have become more or less standard.

10. Strainometers.—A strainometer is a device for measuring strain. If the device measures ten-

sile strain, it is known as an *extensometer*; if compressive strain, a *compressometer*; and if torsional strain, a *troptometer*. The general principle of operation is the same for all. Each instrument consists essentially of two yokes,⁴ which are clamped to the specimen, one at each end of the gage length. As the specimen is strained, the two yokes move relative to one another, and this relative displacement, or some multiple of it, is measured by means of one or more of the following mechanisms:

a. Dial Indicators.—Because of their wide range of applicability dial indicators are discussed more in detail in Art. 13. Figures 8-10 show examples of an extensometer, a compressometer, and a troptometer in which dial indicators are used as the measuring devices.

b. Calibrated Screw with or without Electrical Contact.—A calibrated screw similar to the well-known micrometer may be used to measure the relative displacement of the yokes. To provide delicacy of adjustment, an electrical connection with buzzer is often used to indicate the exact point of contact as the gap representing the displacement is closed by turning the screw.

c. The Optical Lever.—The displacement causes a small mirror to rotate, thus causing a reflected ray of light to travel along a scale. This can be made one of the most precise methods available and is often used when greater sensitivity is desired than is possible with dials or other devices which are often simpler, faster, and easier to use. The Martens mirror extensometer and the Tuckerman optical strain gage both make use of this principle (see Art. 14).

d. Lever and Scale Either with or without Vernier. A straight lever multiplication system may be used, and, while generally this device is not in a class with any of the others mentioned, the Huggenberger tensometer is a notable exception. Lever systems are also used in connection with some of the other devices mentioned.

e. Micrometer Microscope.—If some device such as a pair of needle points can be brought fairly close together from the two yokes, the distance or change of distance between them can be read against the scale of a microscope. The magnification cannot be great in a tubular microscope suitable for hand use, and this device, while very useful in some situations, is impracticable if considerable precision of measurement is needed.

⁴ Although the strain gage discussed in Art. 12 does not have the yokes, it may properly be classed as a strainometer.

f. Scratched Record Read with Compound Microscope.—A sharp needle point attached to one yoke bears lightly against a smoked disk or metal plate

(to an exaggerated scale) that it would take after the specimen is strained. The lower yoke maintains a fixed position with respect to the specimen,

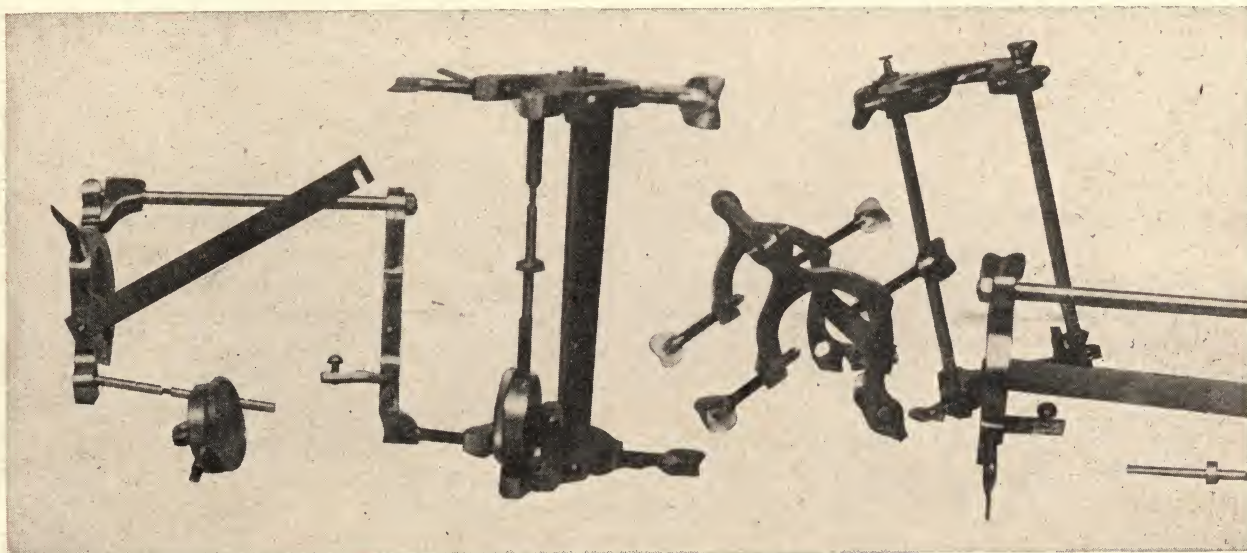


FIG. 8.—Photograph of averaging extensometers.

attached to the other. A record of the relative displacement is scratched on the disk and is read against a scale in a compound microscope. Sometimes the disk is translated or rotated as the test progresses, in order to provide a visible record for varying displacements. The ease of securing an autographic record of rapidly varying displacements has made devices of this class especially useful in studies of impact and other rapidly changing strains. The stremmatograph, the graphic strain gage, and the scratch extensometer are illustrative of this type of strainometer.

11. Operation of an Extensometer.—Figure 11a shows a sketch of a five-point contact extensometer attached to a tensile test specimen. The lower yoke *A* is fastened rigidly to the specimen by means of the three thumbscrews, while the upper yoke *B* is attached by two screws. The rod *C* connects the two yokes, being pinned to them at points *D* and *E*. The spacing bar *F* holds the yokes parallel and at the proper distance apart while the extensometer is being attached to the specimen. The spacing bar must be removed before the specimen is strained. The extensometer shown has a dial indicator *G* attached for measuring the relative movement of the yokes.

The heavy lines in Fig. 11b indicate the position of the extensometer as initially attached to the specimen, and the dotted lines show the position

since it is attached at three points. With the increase ΔL in distance between the ends of the gage length *L* the upper yoke will rotate about the pin *D*, causing the bar *H* to move upward a distance ΔD , which is greater than ΔL . The movement ΔD is measured by the dial indicator.

The ratio by which the extensometer magnifies the total strain in the gage length is called the *multiplication ratio* of the extensometer. The multiplication ratio may readily be calculated as the distance from the pin *D* to the rod *H* divided by the distance from *D* to the points of the screws in the upper yoke.

The gages on some extensometers (especially if the extensometer and gage are purchased as a fully fabricated unit) are calibrated to allow for the multiplication ratio of the instrument, while others are not. If the gage indicates the distance ΔD directly, the total strain in the gage length *L* is found by dividing ΔD by the multiplication ratio.

The extensometer diagramed in Fig. 11 is an example of the "averaging type," *i.e.*, it indicates the average strain throughout the gage length.

In another type of extensometer, the "nonaveraging," the two yokes are not connected by a rod, such as *C* in Fig. 11 but are free to move independently of one another. The relative movement of the lower and upper yokes is measured by two dials (or other measuring devices) 180 deg. apart or by

three dials 120 deg. apart. Since three points determine a plane, it is evident that the three-dial instrument will supply complete data from which

gage length but supplies no information concerning the distribution of strain along the gage length. If, as is usual, the unit strain is calculated as the

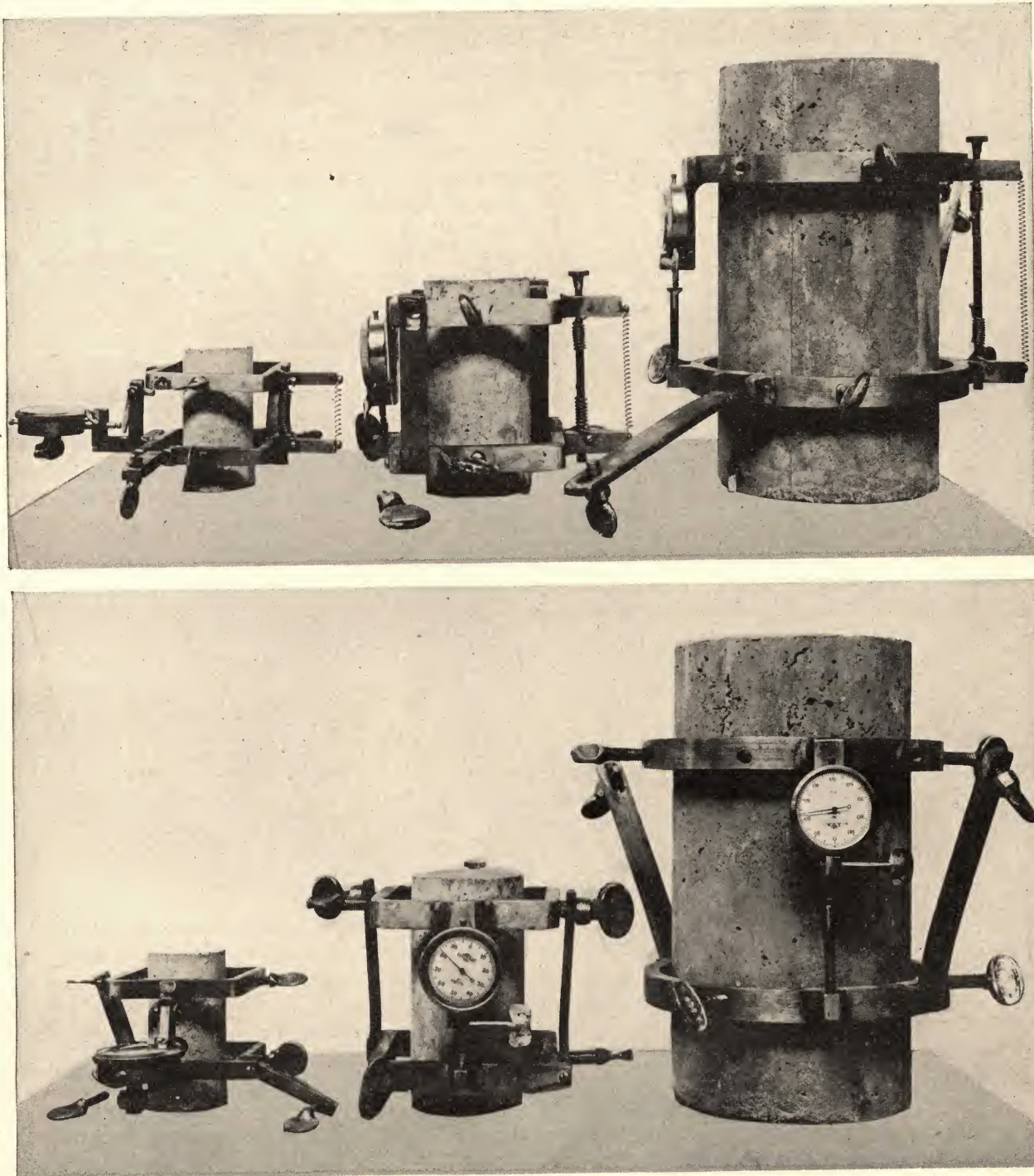


FIG. 9.—Front and side views of three compressometers.

the relative movement of the yokes (the strain) along any element may be evaluated.

Any strainometer indicates the total strain in the

total strain divided by the length over which the strain occurs, only an average value will be obtained.

The maximum unit strain may be considerably

greater than the average, but the value of the maximum cannot be determined from the strainometer reading.

from load or from other causes,⁵ is indicated on the dial, either directly or through a multiplying lever. The Whittemore or fulcrum plate strain gage is an

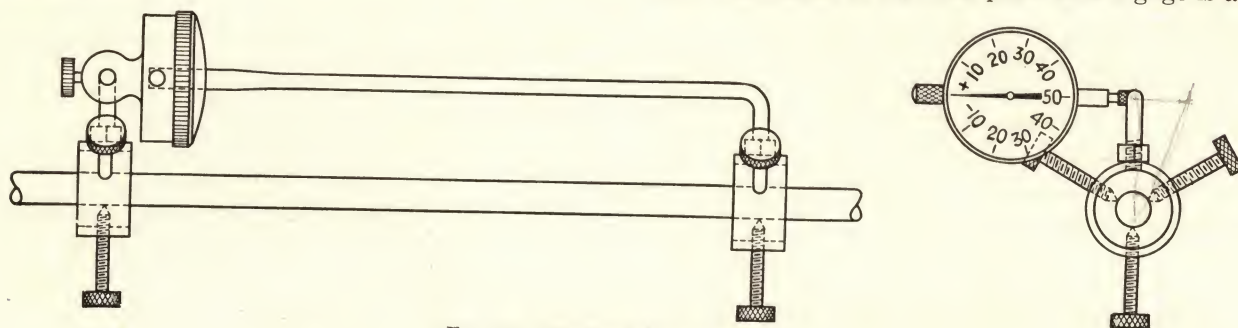


Fig. 10.—Diagram of a troptometer.

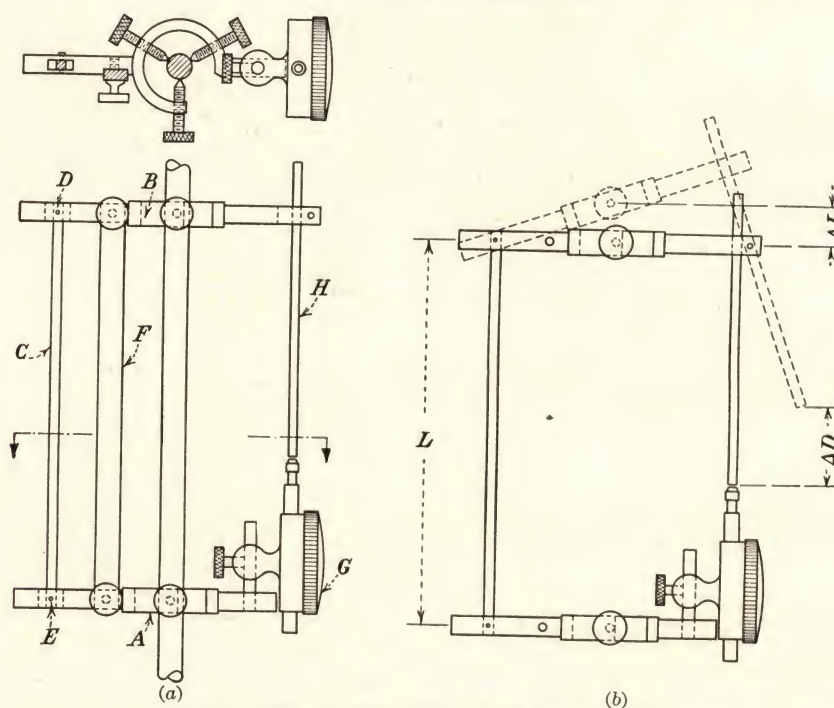


Fig. 11.—Typical extensometer of the averaging type.

12. The Strain Gage.—The strain gage is essentially a portable strainometer. Although it may be attached to a tensile or a compressive specimen and used as an extensometer or a compressometer, it is more often used to measure strains in building frames, trusses, slabs, and other structures in the laboratory or in the field.

The two principal types of strain gages are the direct reading and the multiplying. The essential features of each are indicated in Fig. 12. In both types the conical points are inserted into small (usually No. 54) holes drilled in the specimen, making contact with the rim of the hole. A change in distance between the holes, whether due to strain

example of a direct-reading strain gage, while the lever magnifying principle is used in the Berry and the Olsen strain gages.

In addition to these strain gages there are the Tuckerman optical strain gage, the magnetic strain

⁵ The most common adaptation of the strain gage is for stress determination, but strain gages may be employed to measure strains other than those accompanying stress. They are used to measure the swelling or shrinkage of materials like timber, concrete, or stone under changing moisture content, changes from chemical action or crystal growth, changes from temperature variations, and plastic deformations under sustained loads. To determine strains from any cause, it is necessary either that conditions with respect to other causes be held constant or that separate means be provided for evaluating them.

gage, the Carlson electric strain meter, and others which do not employ dial indicators. Additional information concerning them may be found in the references of Art. 19.

The distinctive feature of the strain gage is its suitability for making successive measurements on a number of gage lines, because it need not be left attached between observations. Thus one instrument may be used to measure strains along an indefinite number of gage lines. Each measured strain is evaluated as the difference between two readings of the gage.

The stresses may be evaluated from the measured strains if the modulus of elasticity of the material is known⁶ and the proportional limit is not exceeded. If the stress over the gage length is not uniform, the strain and stress determined will be the average over the gage length. To secure data for making corrections for changes of temperature, readings may be taken before and after a set of readings on the specimen. Such readings are taken on a carefully laid out gage line on a standard bar of ordinary steel or of invar steel.⁷

Even when temperature changes are unimportant, it is desirable that a reference bar be used in order to detect any alteration in the gage from an accidental turning of the dial or other disturbance. If no suitable reference bar is at hand, each set of readings should end with a duplicate observation upon the first gage line of the set. Any general discrepancy should be apparent if this procedure is followed.

When the strain gage is to be used with wooden members, holes can be drilled in the heads of tacks or small nails at either end of the gage length. In a similar manner, metal plugs can be embedded in concrete. Reinforcement needs to be exposed only near the ends of the gage line where the holes can be drilled in it. Unless the bars are near the surface of the concrete, special gages with legs of greater length may be needed.

⁶ In many cases the modulus of elasticity may be assumed with little error. This is especially true for such a material as steel for which the total possible variation rarely exceeds 10 per cent. In precise work on less uniform materials a more exact value of the modulus may be determined from supplementary tests made on tensile, flexural, or compressive specimens from the same or similar material.

⁷ When readings are being taken on steel, a standard bar of steel similar to that of the member being tested is preferable, since temperature changes affect it the same way as they do the steel member. When a constant, or more nearly absolute datum is desired, invar steel is preferable because of its low coefficient of thermal expansion.

Obvious advantages of the unattached strain gage over other types of strainometers are as follows:

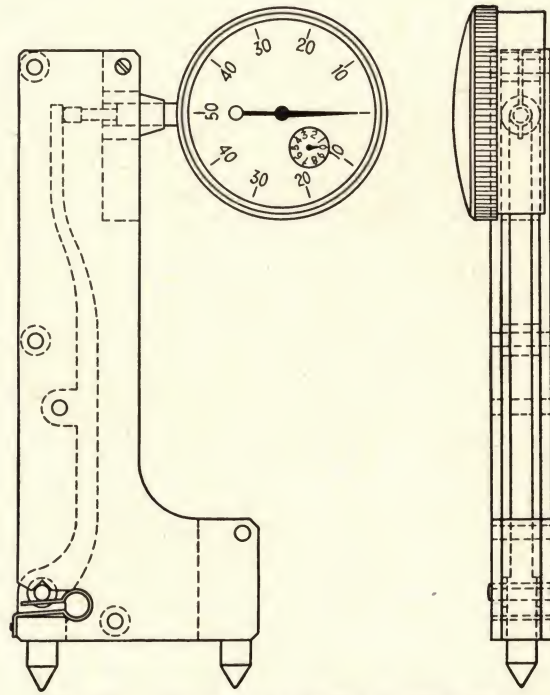


FIG. 12a.—Diagram of a Berry 2-in. strain gage.

a. Readings may be taken over a large number of gage lines which would be costly to equip with fixed instruments. Moreover, fixed instruments would often overlap one another, making it impossible to place instruments on all gage lines simultaneously.

b. Instruments need not be left in place for observations extending over a period of time on members exposed to the weather or to service, where fixed instruments would be likely to suffer damage, loss, or disturbance.

c. Fixed instruments are often difficult to attach to a member in a suitable manner.

d. The strain measured is independent of the strain in any other part of the member.

The greatest disadvantage of the strain gage is the extent to which the personal factor can enter into the taking of readings. Care and experience will obviate much of this.

13. Dial Indicators.—Dial indicators occupy an important place in many laboratory operations where a convenient direct-reading mechanism for measuring short distances is desired. In addition to being widely used on depth gages, thickness gages, and similar measuring or checking devices,

they are standard equipment on many extensometers, compressometers, strain gages, and other laboratory equipment. They are also widely used

gear mechanism and which has a least count of 0.0001 in. However, it has a total range of movement of only 0.02 in., which limits its applicability.

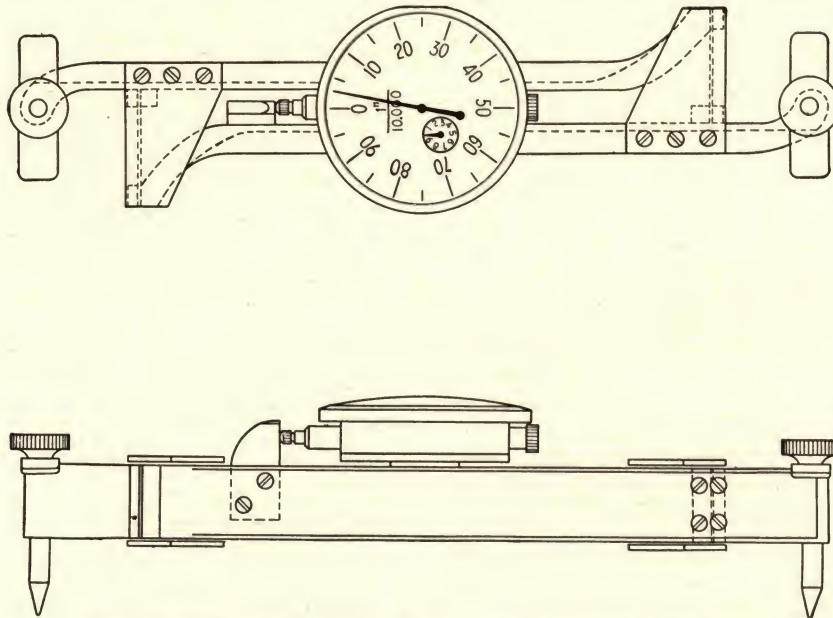


FIG. 12b.—Diagram of a 10-in. Whittemore fulcrum-plate strain gage.

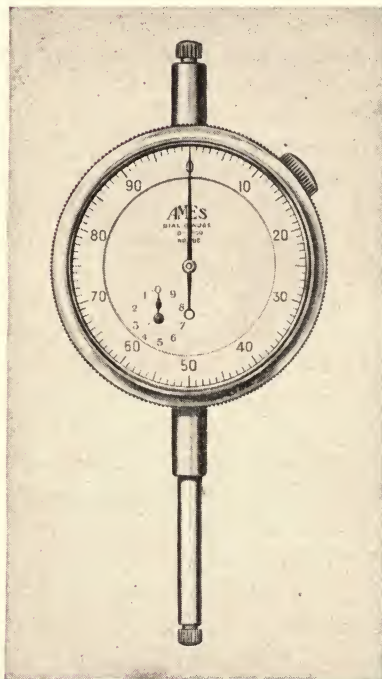


FIG. 13a.—Photograph of a dial indicator. (Courtesy of B. C. Ames Company.)

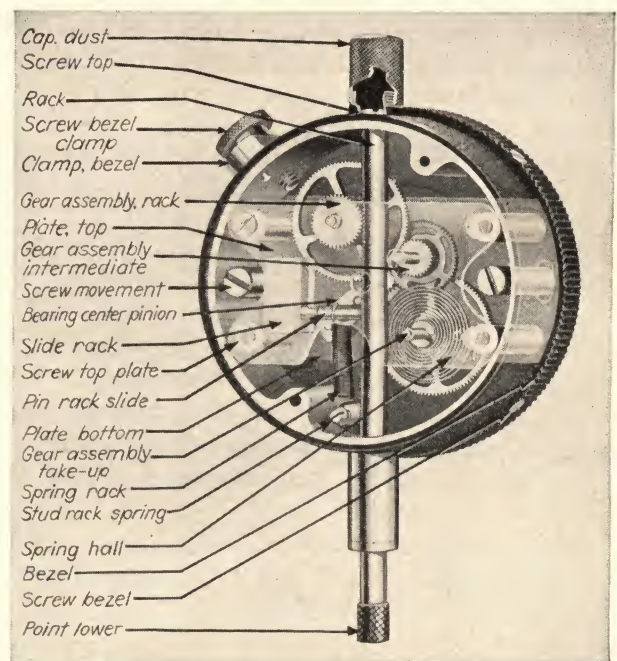


FIG. 13b.—Mechanism of a dial indicator. (Courtesy of Federal Products Corporation.)

for measuring small deflections of beams, frames, etc.

One of the most accurate of the dial indicators is the Last Word dial, which operates with a worm-

The Last Word dial is well suited for use on lateral extensometers for Poisson's ratio determinations because the strains to be measured are small, but it is not well adapted for use with longitudinal

extensometers or strain gages. For these uses dials of other types with a least count of 0.001 in. and a range of about 0.250 in. are preferable.

the change in the gage length. In practice a transit is usually set up at T , the readings being taken on the reflection of the scale in the mirror.

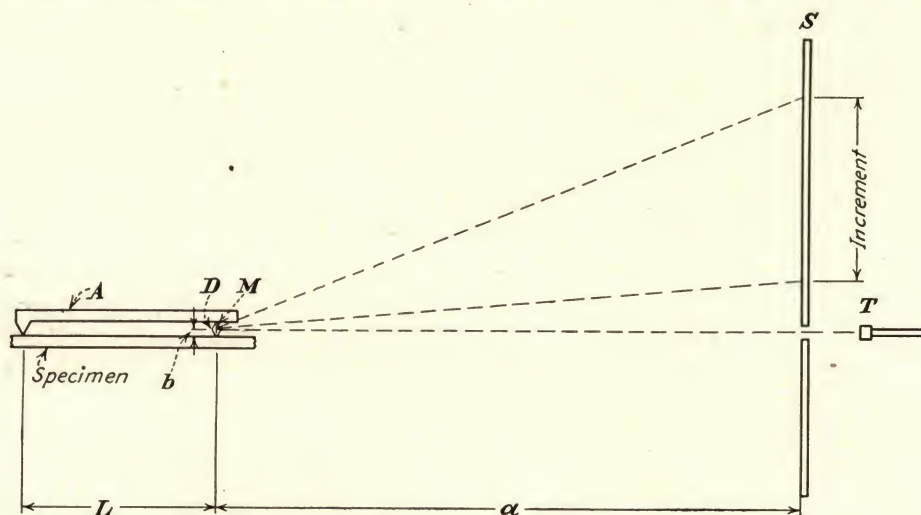


FIG. 14.—Diagram of an optical lever.

The Ames dial, shown in Fig. 13a, and the Federal dial, in Fig. 13b, both of which use a rack-and-pinion mechanism, are available in a variety of models. With a least count of 0.001 in. the total ranges vary from 0.050 to 1.000 in.; the range of 0.250 in. is well adapted to a variety of testing work and is much used. Dials are also available with least counts of 0.00005, 0.0001, 0.00025, 0.0005, and 0.005 in. with ranges from 0.020 to 0.250 in. The rack-and-pinion type of dial indicators is subject to systematic errors, and a 0.0001-in. dial lacks much of being ten times as accurate as a 0.001-in. dial of comparable range.

For convenience of attachment and use, dial indicators are unexcelled within their wide field of application.

14. The Optical Lever.—Figure 14 shows how the optical lever may be used in connection with an extensometer to indicate strains. The extensometer consists of an L-shaped member A and a diamond-shaped member D on which a mirror M is mounted. The extensometer is attached to the member on which readings are desired, the distance L being the gage length. If the test specimen is strained causing the gage length to change, the member D will rotate (counterclockwise for a tensile strain) causing the mirror to rotate through the same angle. Light from a source T is reflected by the mirror on a scale S . Rotation of the mirror causes the light ray to move along the scale, the amount of movement bearing a direct ratio to

The multiplication ratio of the extensometer is equal to a/b and hence may be made relatively large by increasing the distance a . The accuracy of the device is dependent, among other factors, upon the quality of the mirror. Any defect in the mirror will cause a distortion of the readings. Mirrors of polished stainless steel have given good results.

The mirror extensometer, using the optical lever, has the advantages of simplicity, few moving parts, and low inertia. It has the disadvantages of requiring considerable time and care in making the original adjustments and of being very sensitive to external disturbances such as building vibrations.

15. Lightweight Strainometers.—With the increasing need for information concerning strains in machine parts moving at high speeds and subjected to impact or vibration, there has developed a need for lightweight strainometers. For measuring the strains in a rapidly turning airplane propeller, for example, a very light strainometer must be used or the readings will be seriously affected by the mass of the moving parts. The speed of instrumental response to sudden strain is increased as the inertia of moving parts is reduced. To meet the need, there have been developed lightweight measuring devices, among them the scratch recorder.

In the scratch recorder a tiny stylus attached to the specimen at one end of the gage length bears against a target attached at the other end. Movement within the gage length causes the stylus to

scratch on the target a record of the relative movement between the ends. Provision is also made for introducing a lateral movement of the stylus, making possible a continuous record of changing strain. The target is removed at the end of the test, and the record is examined under a measuring microscope.

Another lightweight device, known as the SR-4 Bonded Metaelectric strain gage, consists of a grid of specially selected metal conductors, which is cemented directly to the member under test. The change in conductivity of the instrument when strained under static loading may be measured with a Wheatstone bridge assembly. When impact or vibrational strains are being measured, an oscillograph or pen-and-ink recorder is necessary. Satisfactory results have been obtained for frequencies of strain as high as 30,000 cycles per second.

16. Evaluating Stresses from Strains.—No device has yet been made which will enable one to read the value of a stress at a point. All the so-called "stress-measuring" devices in reality measure strains. However, since the technique of design has been built up around the idea of stress and since the safety of a structural member is judged primarily by the maximum stress in the member, strain readings are usually translated into stresses.

The evaluation of stresses from measured strains is based on the stress-strain relationships for the material in which the strains were measured. Usually, but not always, the stresses are below the proportional limit, in which case the values of Young's modulus and Poisson's ratio are sufficient. For steel and many of the other metals, values for these two elastic constants may be assumed with little error. For materials such as concrete and timber, of which there are many mixtures and kinds, there is a wide range in the possible value of Young's modulus, and the use of average assumed values would be a crude procedure. If the properties are not known accurately supplementary tests should be made to evaluate them.

The first step in the evaluation of stresses consists in eliminating the effects of the incidental variables. Aside from the human errors involved, the strains may be affected by temperature changes, by the inertia of the moving parts of the strainometer or by lag within the specimen. The possible influences of these variables and the techniques for evaluating them depend upon the type of strainometer used.

After the effects of the extraneous variables have been eliminated as far as possible, the stresses are evaluated from the observed or corrected unit strains and the stress-strain relationships. For monoaxial stress, such as normally occurs in beams (at points removed from joints or concentrated loads), columns, and truss members, the stress may be evaluated directly from the stress-strain relationships, provided that the strain is measured in the direction of the stress. If the stress is below the proportional limit, $S = E\epsilon$. For biaxial stress,⁸ such as normally occurs in beams near the load points, in slabs and plates, and in pressure vessels, the evaluation is somewhat more involved because of the fact that stress in one direction is accompanied by strain in all directions. Within the proportional limit the stresses for these cases may be evaluated either algebraically or graphically if both Poisson's ratio and Young's modulus are known. A graphical solution is outlined in the answer to Question 9b (see page 125).

17. The Deflectometer.—Any device for measuring the deflection of a member such as a beam is known as a *deflectometer*. Since deflections are relatively large in comparison with direct strain, deflectometers do not require the same precision of measurement as do strainometers.

A common form of deflectometer is a simple lever with a 1:10 magnification, the short arm bearing against the specimen and the long arm ending in a pointer that travels along a scale. Dial indicators are also convenient and widely used in the measurement of deflections. In the use of deflectometers, special precautions may be required to insure that local crushing of the member or settlement of the supports is not included as part of the measured deflection.

Stresses may be evaluated from deflections as well as from strains. For example, if deflection is caused by bending;

$$S = \frac{Mc}{I}$$

Also

$$\frac{d^2y}{dx^2} = \frac{M}{EI}$$

Hence

$$\frac{d^2y}{dx^2} = \frac{IS}{cEI} = \frac{S}{Ec}$$

⁸ Also for triaxial stress, although the biaxial condition is the only pertinent one of the two here since strains are measured on a free surface—at least in the present state of the art.

Thus, according to the theory of flexure, the stress may be evaluated from a measured deflection curve by successive graphical differentiation. However, the method is not recommended if other methods are available because the percentage errors of original observation may be greatly increased in the process of differentiation and the results secured may be quite misleading.

18. Load-measuring Devices.—Forces or loads may be measured directly or through a lever system by balancing a known weight against the unknown force as is done in an ordinary balance or in a lever-type weighing system, or they may be measured indirectly by observing the displacement which they produce in an elastic member, as is done in the ordinary spring balance.

One of the most convenient of the elastic weighing devices for measuring large loads is the proving ring. It consists of a short cylinder of steel or other suitable material equipped with a device, usually a micrometer, for accurately measuring the change in diameter under load. The proving ring is introduced into the system in such a way that the unknown load passes through it, and the magnitude of the load is evaluated from the change in diameter of the ring. Commercial rings are usually calibrated by means of dead loads of known weight and may be expected to yield satisfactory results for loads not less than 10 or 15 per cent of their rated capacity.

Another type of load-measuring device makes use of the fact that the electrical resistance of carbon changes under pressure. The carbon pile consists of a cartridge of carbon plates connected in series with a source of current and a suitable device for measuring changes in the current. The cartridge is placed so that the unknown load will pass through it and the change in current is noted. When properly calibrated and used under controlled conditions, the carbon pile gives good results, although difficulty has been encountered due to the calibration being somewhat subject to fluctuation.

Almost all load-measuring devices depend upon movement of some sort for the indication of the load. Hence erroneous results may be obtained when the device is used to evaluate loads in a statically indeterminate structure unless the movement of the load-measuring device itself is taken into account. In some situations, such as pressures exerted against bins or retaining walls, a very slight movement often makes the difference

between an active and a static pressure which is sometimes very great.

The friction tape is an ingenious device which meets the need for a measurement of pressure that entails practically no motion or yielding in the direction of the pressure. An alloy steel tape is placed between two plates of metal and calibrated for the frictional resistance developed between the tape and metal housing as the tape is pulled while under varying pressures on the plates. With current techniques the range of variability of results is considerable, but the device has been valuable for securing pressure data in culvert, retaining wall, and slab experiments for which valid data have been very difficult to obtain.

Elastic calibration devices (such as the proving ring) need to have the readings corrected for changes in temperature, and others (such as some types of carbon piles) are subject to fluctuation in calibration with changes in humidity or any shift in the relative positions of adjacent disks.

The Kreuger cell has been used to measure both static and impact pressures and the Goldbeck cell has been used to measure pressures in earth and other granular materials. Both of these devices are described in papers to which references are given in Art. 19. The Brinell ball⁹ may also be adapted to the evaluation of pressures.

19. References on Instrumental Equipment.—The following list of references is appended for the threefold purpose of (a) indicating some of the varied types of instruments that have been devised and used for measuring strains, displacements, and pressures; (b) illustrating the use of such equipment; (c) indicating where additional information may be secured, with a view to procurement, description, or a better understanding of the uses and adaptations.

While the list includes ingenious equipment of many kinds, it is far from complete, for human ingenuity and resourcefulness are almost limitless. The reference or citation for a particular instrument may not be the best, but it should at least provide a tangible clue to desired information.

A. Dial indicators:

1. Last Word: Henry A. Lowe Company, Cleveland, Ohio.
2. Federal: Federal Products Corporation, Providence, R. I.
3. Ames: B. C. Ames Company, Waltham, Mass.
4. Starrett: L. S. Starrett Company, Athol, Mass.

⁹ See Chap. IX on Hardness Tests.

B. Strainometer, autographic attachments, and other testing accessories which are commercially available are listed in the catalogues of the manufacturers of testing machines:

1. Amsler and Company, Schaffhouse, Switzerland. U. S. Agent, Herman A. Holz, New York.
2. Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
3. Riehle Testing Machine Division, American Machine and Metals, Inc., East Moline, Ill.
4. Tinius Olsen Testing Machine Company, Philadelphia, Pa.

C. Strain gages:

1. Berry: Berry, Prof. H. C., Department of Civil Engineering, University of Pennsylvania, Philadelphia, Pa.
2. Whittemore (fulcrum plate): Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
3. Magnetic strain gage:
 - a. Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
 - b. Shamberger, J. Paul. A Magnetic Strain Gage, *Proc. A.S.T.M.*, Vol. 30, Part II, p. 1041, 1930.
4. Tuckerman optical strain gage:
 - a. Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
 - b. Tuckerman, L. B. *Proc. A.S.T.M.*, Vol. 23, Part II, p. 602, 1923.
5. Graphic strain gage (a scratch type):
 - a. Teller, L. W. An Improved Recording Strain Gage, *Public Roads*, Vol. 14, No. 10, p. 189, 1933.
 - b. Richart, F. E., and R. W. Kluge. Tests of Reinforced Concrete Slabs Subjected to Concentrated Loads, *Univ. Illinois Eng. Exp. Sta. Bull.* 314, p. 21, 1939.
6. Brown bubble extensometer:
 - a. Brown, Rex L. A Level-Bubble Strain Gage, *A.S.T.M. Bull.* 93, p. 16, 1938.
 - b. Richart, F. E., and R. W. Kluge. Tests of Reinforced Concrete Slabs Subjected to Concentrated Loads, *Univ. Illinois Eng. Exp. Sta. Bull.* 314, 1939.
7. Fuller-West strain gage: Fowler, C. E. Revision of the Niagara Railway Arch Bridge, *Trans. Am. Soc. Civil Engrs.*, Vol. LXXXIII, pp. 1944, 2018, 1920.
8. De Forest scratch extensometer: Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
9. S. R. Bonded Metalelectric strain gage: Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.

D. Miscellaneous strainometers:

1. Huggenberger tensometer:
 - a. Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
 - b. Voss, R. W. Characteristics of the Huggenberger Tensometer, *Proc. A.S.T.M.*, Vol. 34, Part II, p. 862, 1934.
2. Martens mirror extensometer:
 - a. Text Art. 14.

- b. Withey, M. O., and James Aston. "Johnson's Materials of Construction," 8th ed., John Wiley & Sons, Inc., New York, 1939. (Also available in earlier editions.)

3. Stremmatograph:

- a. Dudley, P. H. Stremmatograph Tests of Unit Fiber Strains and Their Distribution in the Base of Rails under Moving Locomotives, Cars and Trains, *Proc. A.S.T.M.*, Vol. III, p. 262, 1903.
- b. Talbot, A. N. Progress Report on Stresses in Railroad Track, *Trans. Am. Soc. Civil Engrs.*, Vol. LXXXII, p. 1224, 1918.
- c. *Proc. Am. Railway Engrs. Assoc.*, Vol. 19, p. 873, 1918.

4. Interferometer: Houstoun, R. A. "A Treatise on Light," 7th ed., p. 155, Longmans, Green & Company, New York, 1938.

5. Troptometer or torsion meter: Listed in the catalogues of the manufacturers of testing machines (see under B).

E. Deflectometers and other displacement measuring devices:

1. Deflectometer: Listed in the catalogues of the manufacturers of testing machines (see under B).
2. Level-bubble clinometer: Slater, W. A. "Engineering Foundation Arch Dam Investigation," Vol. 1, p. 75, American Society Civil Engineers, New York, 1928.
3. Measuring microscope:
 - a. See catalogues of optical goods manufacturing companies.
 - b. Beggs, George E. An Accurate Mechanical Solution of Statically Indeterminate Structures by Use of Paper Models and Special Gages, *Proc. Am. Concrete Inst.*, Vol. 18, 1922.

F. Pressure measuring devices:

1. McCollum-Peters electric telemeter:
 - a. Baldwin-Southwark, Division of Baldwin Locomotive Works, Philadelphia, Pa.
 - b. Peters, O. S. Recent Developments and Applications of the Electric Telemeter, *Proc. A.S.T.M.*, Vol. 27, Part II, p. 522, 1927.
2. Carlson electric strain meter: Davis, R. E., and R. W. Carlson. The Electric Strain Meter and Its Use in Measuring Internal Strains, *Proc. A.S.T.M.*, Vol. 32, Part II, p. 793, 1932.
3. Kreuger cell:
 - a. Description:
 - (1) Teller, L. W. Accurate Accelerometers Developed by the Bureau of Public Roads, *Public Roads*, Vol. 5, No. 10, p. 1, Dec., 1924.
 - (2) Kreuger, H. Method for Measuring and Calculating the Magnitude of Forces with Particular Regard to Impact Forces, *Trans. 2, Engineering Science Academy*, Stockholm, 1921.
 - b. Applications:
 - (1) Progress Report of Skew Arch Tests, *Public Roads*, Vol. 6, p. 186, 1925-1926.
 - (2) Motor Truck Impact as Affected by Tires, Other Truck Factors, and Road Roughness, *Public Roads*, Vol. 7, p. 69, 1926-1927.

- (3) Effect of Wheel Type on Impact Reaction, *Public Roads*, Vol. 10, pp. 85-94, 1929-1930.
4. Goldbeck cell:
- Goldbeck, A. T., and E. B. Smith. An Apparatus for Determining Soil Pressures, *Proc. A.S.T.M.*, Vol. XVI, Part II, p. 309, 1916.
 - Goldbeck, A. T. Distribution of Pressures through Earth Fills, *Proc. A.S.T.M.*, Vol. XVII, Part II, p. 640, 1917.
5. Brinell ball: (See Chap. IX on Hardness Tests.) (Can be used to measure pressures and to evaluate loads.)
6. Elastic ring (or proving ring):
- Listed in the catalogues of the manufacturers of testing machines (see under B).
 - Richart, F. E., and R. W. Kluge. Tests of Reinforced Concrete Slabs Subjected to Concentrated Loads, *Univ. Illinois Eng. Exp. Sta. Bull.* 314, pp. 15-19, 1939.
 - Bridge Reactions by Proving Rings, *Eng. News-Record*, Vol. 114, p. 446, March, 1935.
7. Friction tape: Spangler, M. G. The Distribution of Shearing Stresses in Concrete Floor Slabs under Concentrated Loads, *Iowa Eng. Exp. Sta. Bull.* 126, 1936.
8. Friction disk:
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NOTES ON TAKING AND RECORDING OBSERVATIONS

20. Cautions on the Use of Measuring Devices.

a. *Mechanical Reversals, Backlash.*—Practically all mechanisms have clearances which introduce slack or backlash when the direction of travel is reversed. This slack constitutes one source of possible error in a measuring mechanism, and it is desirable that there be no reversal in the direction of travel during a series of observations.

b. *Determine the Least Count.*—Note whether the device is calibrated in terms of the motion of the entire assembly or simply of one portion of it.

For example, a dial used in conjunction with a lever mechanism to form a strainometer, if manufactured to be a part of this particular assembly, is probably graduated so as to allow for the influence of the lever; if not, it simply indicates the amount of movement of its own plunger, and allowance must be made for the multiplying effect of the lever mechanism.

c. Direction of Travel.—Note whether the scale readings increase or decrease for change of length in a given direction.

d. Dependable Range.—In many precise measuring devices, observations near either extreme of travel should be avoided. Dials, for example, are likely to be less accurate as either limit of motion is approached.

e. Damage.—Many of the devices are sensitive and subject to damage by a sudden or explosive failure of a specimen. Such instruments should be removed before a test progresses to the stage in which a failure may occur. Damage from jamming may often be avoided by attaching the strainometer in such a manner that travel beyond the range of the instrument simply separates parts normally in contact.

21. Controlling the Precision of Observations.—In work that involves measurement, whether of force, distance, or time, care should be exercised to secure the degree of precision needed without either wasted effort on unwarranted or inconsistent refinements. The following suggestions call attention to some important considerations which, while obvious, are frequently overlooked.

a. Magnitude of the Quantity to Be Measured.—The relative precision of measurements taken with a device having a fixed least count may be expected to increase with the magnitude of the quantity to be measured.

Example.—A scale has a least count of $\frac{1}{32}$ (about 0.03) in. In a measurement of a length of 1 in., the error may be as much as 3 per cent (or even more, owing to the fact that a single measurement usually involves two observations, one at each end of the length measured). If the length were 3 in., the total error would be unchanged, but the percentage error or error per unit of length would be only one-third as great. It follows that an increase of gage length is one of the simplest means of increasing the precision obtainable with a given type of strainometer.

b. Quantities Involving Difference of Measurements.—If the quantities desired are differences

between successive observations, then the precision of measurement may need to be increased materially to attain the desired degree of accuracy.

Example.—The absorption of a 1-lb. sample of stone is to be determined. The saturated sample weighs 1.01 lb., an apparent increase of 1 per cent. With scales having a least count of 0.01 lb., it is evident that there may be present a very high percentage of error in the moisture determination, whereas the weight of the sample itself is accurate within 1 per cent. Scales many times as sensitive would be necessary to determine the moisture content to a degree of accuracy comparable to that with which the weight of the sample itself is known.

c. Measurement in Stages.—In general, the fewer the number of successive operations involved, the greater the gain in accuracy. A nominal 100-ft. length measured with a scale 1 ft. long is less exact than a similar length laid off with a steel tape 25, 50, or 100 ft. in length.

d. Perspective.—A sense of perspective should be cultivated. To measure a timber specimen or a rough cast-iron bar to the nearest 0.001 in. is as ill-advised as to measure a specimen of machined metal only to the nearest 0.1 in.

22. Consistency in Calculations and in Recording Observed Data.—The following points should be kept in mind:

a. Indicate Precision.—Do not record data as if their accuracy were greater than the true precision justified by the measurements.

Example.—If a measurement of a 10-inch length is made to the nearest $\frac{1}{8}$ in. the decimal equivalent should be written 10.1 and not 10.125. The latter gives a misleading indication of an accuracy that is not present. On the other hand, if the measurement is made to the nearest ten-thousandth then it should be recorded as 10.1250. Similarly an even 10, measured with the same precision, should be recorded as 10.0000. For such a number as 1,000,000 the degree of precision is indefinite since the ciphers are necessary to locate the decimal point regardless of whether one, two, or more figures are significant. The number of significant figures may, however, be indicated by writing the number as a multiple of 10^6 . Thus, if there are four significant figures, we may write 1.000×10^6 .

b. Addition and Subtraction.—In addition or subtraction, retain in each quantity one more decimal place than the least precise quantity contains. Drop the final figure in the answer.

Example:

Measured Values	Retained Values
1053.	1053.
12.4	12.4
2.445	2.4
37.51	37.5
1105.355	1105.3

The final figure is then dropped, the result being 1105.

c. Multiplication and Division.—In multiplication or division retain in each factor one more significant figure than is contained in the least precise factor.¹⁰ The number of significant figures in the answer will be the same as the number in the least precise factor.

Example:

Measured Values	Retained Values
3.1416	3.14
2.1	2.1
31416	314
6 2832	6 28
6.59736	6.594

The result is 6.6 in either case.

Since the number written as 3.1416 might be anything between 3.14155 and 3.14164 and 2.1 might be anything between 2.05 and 2.14 their product might be anything between 6.4401775 and 6.7231096. Obviously, two significant figures are all that are justified in the answer.

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SUPPLEMENTARY QUESTIONS

1. In this course frequent reference will be made to A.S.T.M. Standards and Tentative Standards.

¹⁰ In some calculations involving a series of multiplications, additions, divisions, and subtractions, two additional figures may be desirable because of the possible added cumulative effect of discarding or annexing fractional quantities.

- a. Distinguish between these classifications and indicate where each may be found.
- b. Explain the significance of the obvious differences between each pair of A.S.T.M. designations listed below:
 - A70-39 and B70-39.
 - E4-34T and E4-36.
 - A41-12 and A41-36.
 - C18-41 and C19-41.
- c. The books of A.S.T.M. Standards are issued triennially. Each year a number of new Standards are adopted, and others are altered. What nominal precautions will insure contact with the latest that the A.S.T.M. has to offer?
- d. Is it the function of a Standard to justify itself by indicating the reasons for stated requirements?

2. Why should a pressure gage connected to the liquid operating the ram of an hydraulic testing machine be less accurate for measuring the load than a lever-type weighing system or a separate pressure cell through which the applied load must pass?

3. Distinguish clearly between the elementary form of hydraulic testing machine in which a pressure gage is connected to the liquid that drives the ram and the form which uses a pressure capsule, from the standpoints of essential differences in construction, cost, and precision. Indicate some of the probable sources of inaccuracy in the less precise of the two types.

4. Does the type of load-applying or straining mechanism (hydraulic ram or screw gear, for example) influence the accuracy of the results obtained if it be assumed that load can be applied uniformly and at the same rates by the two mechanisms?

5. Are hydraulic-type testing machines ever provided with lever-type weighing systems? Why?

6. Sometimes ordinary hydraulic jacks are used as portable or auxiliary testing machines. Describe two simple kinds of load indicator that could be used with such a load-applying device.

7. Name some of the probable sources of error in a machine which has

- a. A lever-type weighing system.
- b. An hydraulic load-measuring mechanism (pressure gage connected to liquid that propels the ram).
- c. An hydraulic pressure capsule.

- d. A pendulum weighing system similar to that of a common type of torsion machine.
8. The moving parts of instruments that measure strains from impact need especially to be light. Why?
9. a. Is a knowledge of Poisson's ratio needed for the evaluation of stresses from measured axial strain?
- b. Can strain-gage observations be used to evaluate stresses from biaxial and triaxial loading? Explain.
10. A micrometer with least count of 0.001 in. would measure the diameter of a 1-in. bar to within about 0.1 per cent. What percentage error should be expected for the same instrument in measuring the diameter of a $\frac{1}{4}$ -in. bar?
11. A plus or minus error of 100 lb. is about the maximum to be expected in an ordinary 100,000-lb. lever-type testing machine at capacity load. How much error in each of the following devices will give the same maximum percentage error at capacity load as the testing machine:
 - a. In grams for a laboratory balance of 2-kg. capacity.
 - b. In ounces for a platform milk scale (dial type) of 150-lb. capacity.
 - c. In pounds for a 250-lb. capacity platform scale (beam type).
 - d. With representative scales such as those mentioned, is this testing machine a rather crude or a fairly sensitive weighing device? (Many testing machines, especially some of those of large capacity, are relatively much more accurate than the one assumed above.)
12. a. What is the shortest interval of time that can be measured with an error not exceeding 1 per cent if an ordinary watch is used? Assume a total error of 2 sec. in the initial and final readings.
- b. A steel scale having a least count of 0.01 in. is to be used to measure the displacement of the movable head of a testing machine. Through what distance must the head be permitted to travel in order to keep the possible error within 1 per cent? Assume possible initial and final errors in reading to be one whole scale division each.

PROBLEM 1

Study of a Lever-type Testing Machine

A. Object.—To study some of the operating characteristics of a testing machine.

B. References.—Articles 4-7, A.S.T.M. Designation E8-40T, E9-33T. Manufacturers' catalogues.

C. Preliminary.—Study the machine assigned giving special attention to each of the following features. (No written record is required of the results of this preliminary study.)

1. Starting, stopping, reversing, and speed controls.
2. Straining mechanism.
3. Provision for taking care of eccentric positioning of specimen in the machine.
4. Provision for adjusting the plane of the head to parallelism with the plane of the end of the specimen in compression tests.
5. Provision for gripping tensile specimens.
6. Methods of transferring load to weighing system in tension and compression tests.
7. Weighing or load-measuring mechanism.

8. Provision for absorbing the stored energy suddenly released at rupture (recoil).

D. Determinations to Be Made and Recorded.

1. Types of test for which the machine may be used.
2. Maximum size of specimen of each type which the machine can accommodate without reductions for grips, bearing blocks, or other accessories.
3. Multiplication ratio (if the machine is of the lever type) or equivalent arm (if it is a torsion machine).
 - a. By measurement.
 - b. By weight.
4. Speeds (in inches per minute) of movable head when the machine is running free, or, if the machine is hand-operated, the number of turns of the crank or handwheel per inch of movement of the head.

E. Procedure.—Note each of the features listed in Item C. Make and record the observations necessary to determine each of the characteristics listed in Item D. In taking measurements use

methods which will keep the probable errors of observation within 1 per cent. If the machine has its platen supported by a double lever system, follow each system through to their junction point and note whether or not the two multiplication ratios are the same. After checking over the measurements and calculations, if necessary, until essential agreement has been reached, the mean value for the multiplication ratio to that point will be used in the remaining computations unless the measurements for one of the systems were more difficult to make than for the other. In that case carry forward the ratio that has been determined with the greater accuracy.

F. Report.

1. Tabulate the characteristics of the machine.
2. Draw a dimensioned straight-line diagram showing the lever system with the poise at capacity load.
3. With the aid of two free-body sketches of the scale beam, one for the beam balanced at zero load and the other for the beam balanced at capacity load, demonstrate that the multiplication ratio of the scale beam is equal to the length of the scale divided by the short arm of the scale beam.

G. Supplementary Questions.

13. a. What factors may have contributed to error in the determination of the multiplication ratio
 - (1) By measurement?
 - (2) By weight?
- b. Which method is believed to have given the more accurate determination?
14. Does the movable head travel in the same direction in a compressive test as it does in a tensile test? Why?
15. If a specimen is not centered on the platen of a machine having a lever-type weighing system, is the multiplication ratio altered thereby? Why?
16. Should temperature fluctuations alter the multiplication ratio?
17. Is the multiplication ratio of a machine with a lever-type weighing system subject to much fluctuation?
18. For machines with a lever-type weighing system the load is indicated only when the beam is in balance. What is known about the magnitude of the load when
 - a. The beam is down?
 - b. The beam is at the upper limit of its travel? Why should the beam never be allowed to remain at the upper limit of travel?
19. For the machine studied, approximately how far is the bed of the testing machine depressed for 1 in. of movement of the free end of the beam?
20. Why is it more hazardous to the testing machine to place a load of 5000 lb. on a solid block of cast iron than on a helical spring or a block of wood? Indicate clearly the essential distinction that creates the greater hazard with the block of iron.
21. Why is it always desirable and usually necessary to remove a load at a speed not higher than was used in its application?
22. Should carefully centered cylindrical pivots (pins) be a satisfactory substitute for knife-edges in a lever-type weighing system? Explain.
23. What is the current trend with respect to the use of lever-type weighing systems on testing machines?
24. a. Some lever-type testing machines are provided with two poises, the smaller weighing one-tenth of the larger. With a machine on which the scale beam is graduated for the larger poise, can the smaller poise be used successfully by simply substituting the smaller poise for the larger one and dividing the beam readings by 10?
- b. Explain.
- c. Is the multiplication ratio of the weighing system changed when the smaller poise is used?
25. Occasionally the parts of a lever-type machine have been made heavy enough to permit doubling its capacity by hanging a weight (furnished with the machine) from a hook provided at the end of the scale beam.
 - a. Within what range can the machine be used with the supplementary weight hung from the end of the beam?
 - b. Can it be balanced at zero with the weight in place?
 - c. Is using the extra weight analogous to replacing the poise by one twice as heavy?
 - d. Explain.
 - e. Within what range of load can the machine be used with the supplementary poise (as discussed in the preceding question)?

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PROBLEM 2

Calibration of a Testing Machine

A. Object.—To compare the actual loads on a testing machine with the loads indicated by the weighing system.

B. Special Apparatus.—Proving levers and standard weights or other calibration devices.

C. References.—Articles 4-7. A.S.T.M. Designation E4-36.

D. Determinations to Be Made.

1. The correction that should be made to the indicated load for each load applied.

2. The sluggishness (or sensitivity).

E. Procedure.

1. *Preparation for the Test.*—If proving levers are used take measurements to determine their multiplication ratio and determine the tare force exerted on the platen by the levers and pans.¹¹ Adjust the counterpoise (or movable scale if an hydraulic machine is being calibrated) in order to produce an initial reading of 0 lb. Insert the levers in the proper position and adjust the movable head until the plane of the knife-edges is horizontal.

2. *Performance of the Test.*

a. For a lever-type weighing system, bring the beam to balance near its upper limit of travel and record the total load. For increasing loads the beam should always be balanced by advancing the poise to eliminate errors due to backlash in the mechanism. If the poise is overrun and the beam drops too far, back the poise more than is necessary to balance the beam and repeat, more cautiously, the attempt to balance. Take a reading for the sluggishness by advancing the poise until the beam drops approximately $\frac{1}{2}$ in.¹²

Apply and remove the load in 10 approximately equal increments, recording for each the indicated reading (load at point of initial balance) and also a reading for sluggishness. For decreasing loads the initial balance will be near the bottom of travel of the beam, and a reading for the sluggishness will be obtained with the beam approximately $\frac{1}{2}$ in. higher.

¹¹ The correct placement of the levers is illustrated in Fig. 1 of A.S.T.M. Designation E4-36. The load due to the levers themselves plus the unloaded baskets or trays can be measured by substituting an elevated pair of platform scales for the weighing table of the machine and an improvised framework or bearing for the crosshead. One such determination should suffice as long as the levers and trays are not altered.

¹² The test for sensitivity, as described for the hydraulic machine, may be substituted for the sluggishness.

b. For an hydraulic weighing system, read the indicated load directly. Obtain a reading for the sensitivity by adding measurable weight directly to the table of the machine until a movement of the needle is detected. The added load may be taken as a measure of the sensitivity. Apply and remove the load in 10 approximately equal increments, recording the indicated load and sensitivity for each increment.

If a proving ring is used instead of the levers, make at least two observations on the indicating mechanism of the ring for each increment of load. Also record the air temperature of the laboratory.

F. Report.

1. *Graph Sheet.*—Plot corrections as ordinates against the total loads indicated by the machine as abscissas.¹³ (If the load indicated by the machine is too large, the correction is negative and should be plotted downward from the zero line.¹⁴) Use different point symbols and different types of lines for the curves for ascending and descending loads. Plot a similar curve showing the average value of the sluggishness (or sensitivity) for each increment. Draw in the lines indicating the maximum correction permitted by A.S.T.M. Designation E4-36.

2. *Results.*—Indicate the portions of the loading range covered by the test in which the machine meets the A.S.T.M. requirements for accuracy.

G. Supplementary Questions.

26. What are some of the possible sources of error in the machine calibrated?

27. Name in order of relative accuracy four methods of calibrating a testing machine. State the limitations of each method.

28. A simple and easily used calibration device is an alloy steel ring to which load may be applied along a diameter. The measured flattening of the ring varies with the load on it, which may be known from a previous calibration of the device. Under which of the four methods mentioned above should the calibration ring be classified?

29. In the machine tested did the error seem to vary with the load? In what range of loading was the machine most accurate? Least accurate? For a given magnitude of error is the accuracy a

¹³ If proving levers are used, treat the tare load produced by the levers as the first increment.

¹⁴ Place the zero line in such a position that the data can be shown to the best advantage.

function of the load or is it independent of the load?

30. Define the terms tolerance, error, and correction as they are applied to testing machines.

31. What are the permissible tolerances set by the A.S.T.M. for the weighing systems in machines that measure load? Is it proper to report a blanket acceptance or rejection of a testing machine? Explain.

32. Distinguish clearly between accuracy and sensitivity. Is a sensitive machine always accurate? May an accurate machine be sluggish? Name factors other than sluggishness which may influence the accuracy of the machine studied.

33. How should dulled or dirty knife-edges affect the load reading

a. When balance is attained by advancing the poise?

b. When the beam is balanced by backing up the poise?

34. Should inertia as a source of inaccuracy be influenced by the acceleration or deceleration of load as a test progresses?

35. For what types of machines is inertia likely to be an important consideration?

36. Is there any essential difference between sluggishness and sensitivity?

PROBLEM 3

Study of a Strainometer

A. Object.—To determine the multiplication ratio of an assigned strainometer throughout its range of motion.

B. Special Apparatus.—Compressometer (or other form of strainometer) and calibrator (see Fig. 15).

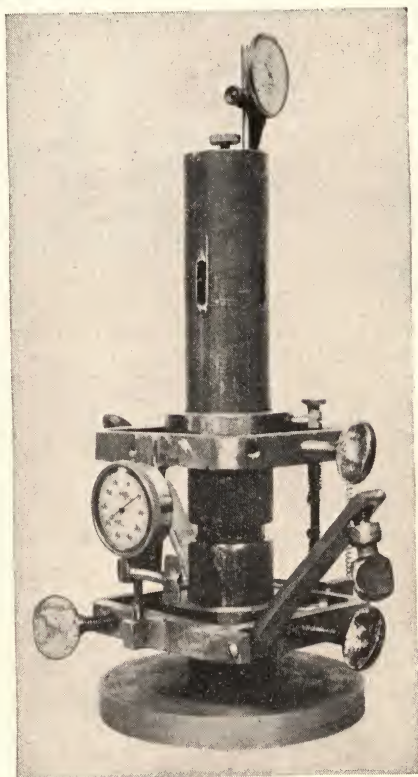


FIG. 15a.

FIG. 15a.—Calibrator with a 3-in. diam. compressometer in position for calibration. Compressometer is being calibrated against the "Last Word" dial attached to the core or central shaft and activated by the sliding sleeve. The top thumbscrew raises or lowers the sleeve. (Calibrator devised by H. J. Gilkey and Fredrik Vogt of Trondheim, Norway.)

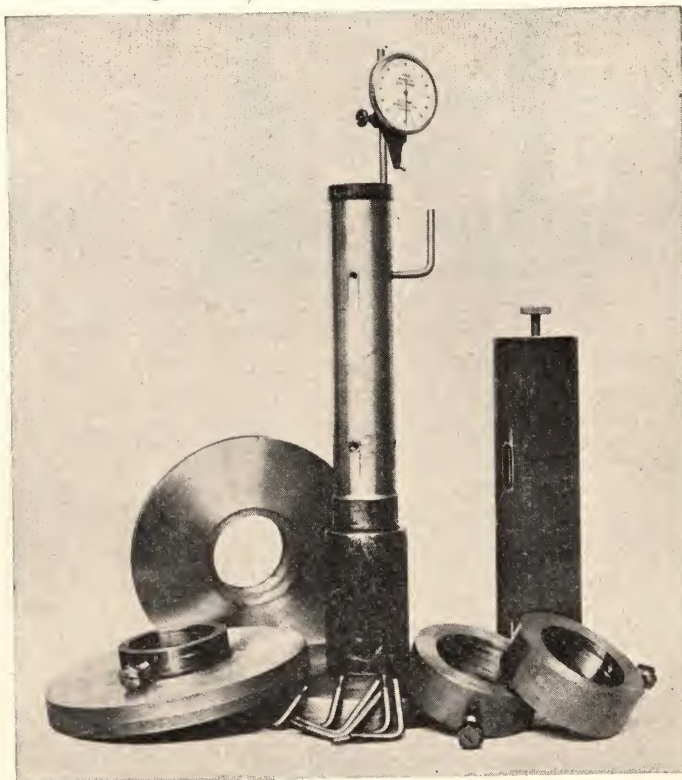


FIG. 15b.

FIG. 15b.—Calibrator disassembled. Essential parts are the core, the fixed sleeve below and the sliding sleeve above. A calibrated micrometer screw could be used instead of the dial as a standard for comparison. The collars are for the attachment of 6-in. and 3-in. diam. compressometers which span the gap between the fixed and movable sleeves. The L rods are for the attachment of dials to be calibrated. The L rods extend through slots in the movable sleeve to screw into the fixed core. The dial plungers then bear against one of the larger (6-in.) collars which is clamped to the movable sleeve.

C. Determinations to Be Made.

1. Multiplication ratio by measurement with a steel scale.

the plunger. Adjust the dial on the top of the calibrator to accommodate the full range of the compressometer.

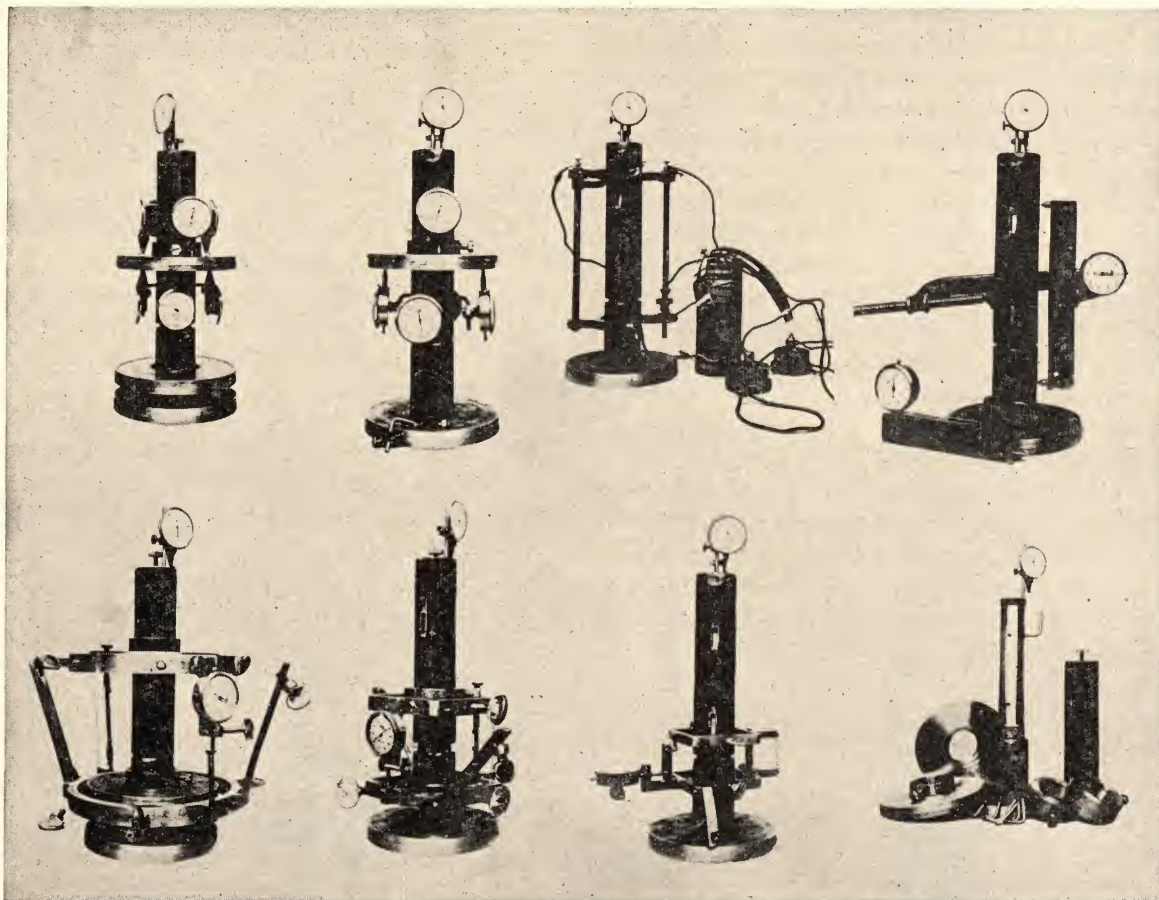


FIG. 15c.—Adaptations of a calibrator. Calibrator set up for calibrating against a "Last Word" dial: (1) "Last Word" dials (8 at one time); (2) several dials of the Ames or Federal type; (3) an electrical contact 8-in. micrometer-screw extensometer (suitable for use on metal bars); (4) an 8-in. Berry strain gage (held in position with a carpenter's clamp); (5) a 6-in. diam. compressometer (suitable for use on 6- by 12-in. concrete cylinders); (6) a 3-in. diam. compressometer (suitable for use on 3- by 6-in. concrete or mortar cylinders), similar to Fig. 15a; (7) a 2-in. diam. compressometer (suitable for use on 2- by 4-in. mortar cylinders); (8) calibrator disassembled, similar to Fig. 15b.

2. Multiplication ratio by calibrator.

D. Reference.—Articles 9–16.

E. Procedure.¹⁵

1. *Preparation for the Test.*—With a steel scale make the measurements necessary for the determination of the multiplication ratio of the compressometer, which is defined as the ratio of the movement indicated by the dial to the corresponding total strain in the gage length.

Attach the compressometer to the collars on the calibrator, and release the spacing bars. Adjust the connecting rod at the back until the yokes are parallel. Turn the thumbscrew against which the dial plunger acts until it just makes contact with

¹⁵ The details will vary somewhat with the form of strainometer to be calibrated.

2. *Performance of the Test.*—Record initial readings on the compressometer dial and on the calibrator dial. Determine the total range of movement of the compressometer dial, and select increments which will insure 10 readings within the range of motion. Using these increments, take readings on both dials to the limit of motion of the compressometer dial. Reverse the motion and take readings, making the first increment one-half of the ascending increments in order to stagger the observations.

F. Report.

1. *Graph Sheet.*—Plot the total movements of the compressometer dial as ordinates against movements of the calibrator dial as abscissas. Place on the same sheet the line representing the cor-

responding relationship as obtained by measurement with the steel scale.

2. *Results.*

- a. Give the value of the multiplication ratio as determined from
 - (1) Measurement with the scale.
 - (2) The calibrator.
- b. Give the value of the constant by which one dial division should be multiplied to obtain the corresponding unit strain as determined from
 - (1) Measurement with the scale.
 - (2) The calibrator.

G. **Supplementary Questions.**

37. What errors may have been present in each of the methods?

38. Which method should be the more accurate?

39. Does the compressometer have any features which would make frequent recalibration necessary?

40. Assume that the compressometer calibrated was of the averaging type, being hinged at the back. In such an instrument how does the movement recorded by the dial compare with the actual change in length of specimen (between the yokes)?

41. In another type of strainometer the yokes are independent, each having at least three points of attachment to the specimen. The relative move-

ment of the yokes is measured by means of dials or other measuring devices along two elements 180 deg. apart or along three elements 120 deg. apart. For a given unit deformation should these dial readings be the same as they were on the instrument that was calibrated? Discuss the relative merits of the one-, two-, and three-dial arrangements.

42. Determine the percentage error involved in the unit strain if an error of 0.01 in. is made in

- a. The gage length.
- b. The dial readings.

43. A specimen is tested with a strainometer which is inaccurate by a constant factor. Which of the following properties will be in error? Explain.

- a. Ultimate strength.
- b. Proportional limit.
- c. Yield point (if the material has one)
- d. Young's modulus.
- e. Poisson's ratio.
- f. Modulus of resilience.
- g. Work of rupture.
- h. Yield strength.
- i. Rupture stress.
- j. Elastic limit.

44. Should the multiplication ratio of the strainometer calibrated vary with variations in temperature?

CHAPTER II

PROPERTIES OF MATERIALS

24. Introduction.—For known states of stress, the performance of a material may usually be predicted if its properties are known. For many of the uses of a material the essential properties are few in number and are easily determined. As new uses or needs arise other properties become significant, and methods of testing for them must be developed. Those properties which are most frequently evaluated from physical tests are an index of the elastic strength, the ultimate strength, and for metals, some measure of ductility. The evaluations of other properties, such as modulus of elasticity, Poisson's ratio, hardness, resilience, toughness, endurance limit, and creep limit, require additional equipment and effort. Generally speaking, such important attributes as corrosion resistance and other forms of durability cannot be expressed in terms of a single property or be measured or determined by short-time laboratory test. The following discussions of essential properties are introduced primarily for reference and are necessarily brief. The student should refer to his textbooks on materials and mechanics of materials for supplementary treatments.

25. Stress.—Stress,¹ or unit stress, is the intensity of resisting force (usually measured in pounds per square inch) developed within a material under load. Stresses may be developed in tension, compression, or shear.

Stress is a state or a condition rather than a property, but the magnitudes of the stresses under certain conditions are measures of such important properties as elastic strength and ultimate strength and contribute to the values of such other properties as stiffness, resilience, and toughness.

26. Strain.—Strain, unit strain, or unit deformation, is the change in dimension per unit² length of member. It is a ratio of two lengths and thus is a pure number, having no units.² Without quali-

¹ Without qualification the term *stress* denotes *unit stress* except in truss analysis where stress usually refers to the *total stress* (or force in pounds) developed by the truss member.

² Strain is often designated as *unit strain* (or *unit deformation*) in *inches per inch*. This form of designation should be avoided, although it is redundant rather than wrong.

fication "strain" means "unit strain" or unit deformation.

Strain, like stress, is a state or condition rather than a property, but the magnitudes of strains under certain conditions are measures of such properties as percentage elongation and percentage reduction of area and contribute to the values of such other properties as stiffness, resilience, and toughness.

27. Strength.—Resistance to applied force. Measured in pounds for the total strength of a member or in pounds per square inch as the unit strength of a material. As applied to a material, it is the highest unit stress which the material will develop without failure. Since failure may occur by slip, by creep, or by fracture and since steady impact, or repeated loads produce different effects upon materials, different properties are required to define strength under each of the conditions. The manifestations of strength of interest to the engineer are elastic strength, ultimate strength, rupture strength, endurance limit, creep limit, modulus of resilience, and modulus of toughness, any of which may be in tension, compression, or shear. Important strengths are discussed in articles that follow.

28. Elastic Strength.—"A limiting stress below which the permanent distortion of a material is so small that the structural damage is negligible, and above which it is not negligible."³ It may also be defined as the highest unit stress which the material will develop without excessive slip. It is of importance to the engineer in designing structures or machine parts in which a minimum of permanent distortion is permissible. Such a limiting stress can be approximated with varying degrees of exactness. Several more or less easily determined properties have been suggested as indexes of elastic strength, each with its particular advantages and disadvantages. Some of them are as follows:

The designation is a proper and necessary one for cases of mixed units such as inches per foot or inches per mile. In materials testing mixed units are rarely used.

³ Moore, H. F. "Textbook of the Materials of Engineering," 5th ed., p. 21, McGraw-Hill Book Company, Inc., New York, 1936.

a. Elastic Limit.—"The greatest stress which a material is capable of developing without a permanent deformation remaining upon complete release of the stress"⁴ (pounds per square inch). Its evaluation involves repeated application and removal of load and the use of very sensitive measuring devices. In general the determination is not practicable.

b. Yield Point.—"The stress in a material at which there occurs a marked increase in strain without an increase in stress"⁴ (pounds per square inch). This definition fails to distinguish between the yield point and the ultimate strength, at which for many materials there is also a marked increase in strain without an increase in stress. The ultimate strength is never to be considered a yield point. When there is a yield point, its value will normally be from 50 to 75 per cent of the ultimate strength. Only a ductile material can have a yield point, although it does not follow necessarily that all ductile materials have yield points. For ferrous metals with well-defined yield points, there are available three simple methods of determination which give results that are in excellent agreement one with another and none of which require stress-strain diagrams. They are yield point by drop of beam, yield point by dividers, and yield point by scaling.

DROP OF BEAM.—With many materials the yielding or pronounced increase in length results in the load decreasing sufficiently to cause the beam of a lever-type weighing system to drop momentarily. From this phenomenon the term yield point by drop of the beam has arisen. The "drop of the beam" method has been and still is much used for evaluating the yield point commercially. The expression "halt of the needle" or "halt of the gage" corresponds, for an hydraulic weighing system, to drop of the beam for lever-type weighing systems.

DIVIDERS.—For all steels which have yield points, a strain of 0.005 lies within the yield-point range of deformation. In an 8-in. gage length this amounts to 0.04 in. If a pair of dividers is set for 0.04 in. more than the original gage length, the yield point can be determined by noting the load at which the gage length corresponds to the span of the dividers.

SCALING.—Hot-rolled ferrous metal is covered with a brittle coating of iron oxide (mill scale). The plastic deformation of the bar within the yield-point range of stress cracks the more brittle oxide layer and causes it to scale off. A reading of the

load when scaling occurs constitutes, therefore, the third means of detection. The scaling has generally been used as a check on the drop of the beam determination rather than as a method in itself. The phenomenon of scaling at the yield point sometimes supplies valuable information regarding parts of a structural element that may have been overstressed. Materials which have been cold worked (such as cold-drawn wire, cold-twisted or cold-rolled bars) have already lost their scale, but in most cases they have also lost their yield point from strain hardening.

c. Proportional Limit.—(Sometimes called *proportional elastic limit*.) "The greatest unit stress which a material is capable of withstanding without a deviation from the law of proportionality of stress to strain (Hooke's law)"⁴ (pounds per square inch). This may be determined directly from the stress-strain diagram as the stress at the upper end of the straight-line portion. The determination of the proportional limit requires stress-strain data, and its value will depend upon the refinement of the data, the scale used in the plotting, the selection of the straight line through the plotted points, and, of greater importance, the shaping of the curve to join the tangent or straight-line portion.

d. Johnson's Apparent Elastic Limit.—The stress (pounds per square inch) at which the slope of the stress-strain diagram is 50 per cent greater with respect to the axis of stress than is the initial slope. The determination requires a stress-strain diagram and the selection of an initial tangent, but differences in scales and refinement of observations and plotting have much less effect upon Johnson's apparent elastic limit than upon the proportional limit. The method of determining Johnson's apparent elastic limit from a stress-strain diagram is shown in Fig. 16.

e. Yield Strength.—"The stress at which a material exhibits a specified limiting permanent set"⁴ (pounds per square inch). The yield strength is determined from the stress-strain diagram as described in A.S.T.M. Designation E6-36 or E8-40T. The offset method as there recommended may be outlined as follows:

On a stress-strain diagram a previously specified offset is laid off along the strain axis. A line is drawn through this point parallel to the initial tangent of the stress-strain diagram. The stress corresponding to the intersection of this line with the stress-strain diagram is taken as the yield strength. The stress that represents the

⁴ A.S.T.M. Designation E6-36.

yield strength will, in general, vary with the value selected for the offset.

The specified limiting offset is taken as a limiting value

the yield strength of most materials varies with the offset, the value of offset used should be stated in reporting the yield strength.

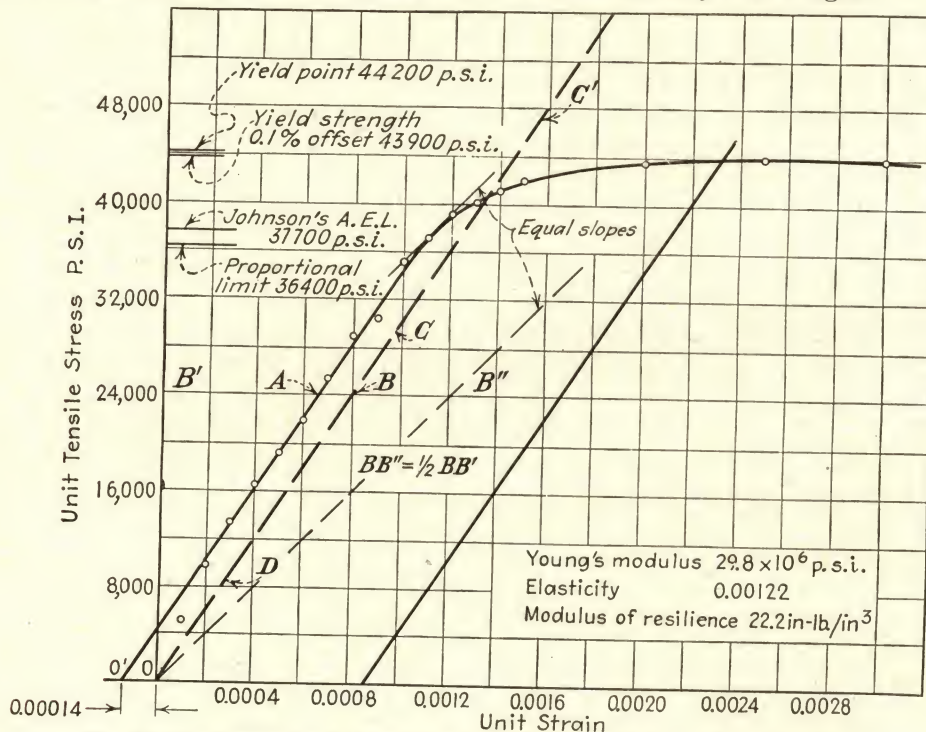


FIG. 16.—Lower portion of a typical stress-strain diagram for mild steel in tension.

of permanent set below that which is believed to be objectionable for normal use. For general use the following offsets have been recommended tentatively. The values are expressed as unit strains generally given as percentages for convenience in writing.

Steel in tension.....	0.20 per cent or $\epsilon = 0.0020$
Aluminum alloys in tension..	
Magnesium base alloys in tension	
Malleable iron castings in tension	0.35 per cent or $\epsilon = 0.0035$
Brass in tension.....	
Bronze in tension.....	
Gray cast iron in tension.....	0.05 per cent or $\epsilon = 0.0005$
Wood in compression parallel to the grain.....	0.05 per cent or $\epsilon = 0.0005$
Concrete in compression.....	0.02 per cent or $\epsilon = 0.0002$

The method of evaluation of the yield strength is based in part on the observation that, for most materials, the unloading curve from any stress is approximately a straight line parallel to the initial tangent. Hence, the offset is approximately the permanent set which would result from the material being unloaded after stressing it to the yield strength. The proportional limit is the yield strength for 0.00 per cent offset. Since the value of

29. Ultimate Strength.—The maximum computed stress which a material is capable of developing under a slowly applied load. It is usually expressed in pounds per square inch.

a. Axial Ultimate Strength.—The term *ultimate strength* usually refers to the condition of axial loading or pure shear and is computed as the maximum load carried (prior to failure) divided by the original area or cross section of the member or specimen over which the stress is distributed.

b. Modulus of Rupture.—The modulus of rupture is a measure of the ultimate strength in bending and is calculated from the flexure formula using the maximum resisting moment developed by the beam prior to failure in flexure. The exact flexural ultimate strength cannot be obtained directly since the flexure formula is valid only for stresses below the proportional limit; hence the modulus of rupture is a *fictitious ultimate flexural strength*. While in no sense a correct ultimate fiber stress for the material, it does serve a useful purpose in comparing beams of different materials and sizes. In general, beams of similar proportions will have moduli of rupture proportional to the ultimate strengths of the materials composing them. The modulus of rupture is

rated as one of the significant physical properties of such materials as cast iron, concrete, stone, timber, porcelain, and brick.

c. Modulus of Rupture for Torsion.—The modulus of rupture for torsion is a measure of the ultimate strength in torsion and is calculated from the torsion formula using the maximum torque developed by the member. Although the torsion formula is invalid for stresses above the proportional limit in shear, the ultimate torsional resistance of circular members can be compared on the basis of this fictitious ultimate shearing stress computed from the torsion formula.

d. Ultimate Shearing Strength.—The ultimate shearing strength of rivets and pins is usually calculated as the total load divided by the cross-sectional area. Since the stress is not uniformly distributed in such members, the result is in reality an average shearing resistance rather than a maximum stress.

For rectangular beams the ultimate shearing strength may be taken as three halves of the maximum shearing force divided by the area, and for a circular beam the ultimate shearing strength may be taken as four-thirds of the average. These calculations assume that the stress distribution is the same at the ultimate as it is below the proportional limit. The assumption is incorrect, but the results form a satisfactory basis for comparing the maximum resistance of beams to shear.

30. Rupture Strength.—The stress (pounds per square inch) at which an axially loaded specimen fractures under slowly applied load. For brittle materials the rupture strength may be regarded as identical with the ultimate strength, but, for ductile materials tested in tension, the rupture strength is usually below the ultimate, as computed in the standard manner from the original cross section. If the load at rupture is divided by the final (reduced) area of cross section at the break, the quantity obtained will exceed the ultimate strength, which indicates that the reduction in the resistance offered by the specimen after the ultimate strength was passed is due to reduction in cross-sectional area rather than to a lowering in the strength of the material as rupture approaches. In a torsional test of ductile as well as brittle material the ultimate and rupture strengths are identical since there is no reduction of area by necking prior to failure.

31. Ductility.—The capacity for taking plastic deformation in tension. This is usually a desirable quality in that ductile materials are able to adjust

themselves to local or general overstrain without fracturing. Ductility combined with strength results in toughness which gives resistance to failure under impact. Normally, ductility refers to the plastic deformation that accompanies an ordinary short-time test if the stress extends beyond the elastic limit of the material. The commonly accepted measures of ductility are as follows:

a. The percentage elongation in a specified gage length of a tensile specimen tested to fracture.

b. The percentage reduction in the cross-sectional area of a tensile specimen at the section at which fracture occurs.

Obviously both of these measures are expressed as ratios and are without units. For metals (practically the only structural materials for which ductility is considered to be present as a significant property) tests are usually on a 2-in. or an 8-in. gage length. For such ductile materials as mild steel the percentage elongation in 2 in. is higher than in 8 in. because of the high localized elongation that occurs in the immediate vicinity of the fracture. It is necessary, therefore, that the gage length always be stated in referring to percentage elongations, *i.e.*, "percentage elongation in 8 in." Bend tests provide practical, though somewhat crude, measures of ductility.

Another manifestation of ductility is the creep, often referred to as *flow*, that occurs under sustained loading. The plastic action may either continue until the material fails or diminish with the lapse of time under load, depending upon the material and the magnitude of the stress. While important in connection with many of the engineering uses for materials, especially at high temperatures, the phenomenon of plastic flow has not yet reached the stage of ready laboratory evaluation.

32. Elasticity.—The capacity of a material for taking elastic (recoverable) deformation. The elasticity of a material may be evaluated as the unit strain of the material at its elastic limit, *i.e.*, it is the maximum unit strain to which the material may be subjected without having measurable permanent set upon removal of the load. As a matter of convenience the elasticity is commonly evaluated at the proportional limit.

The property *elasticity* used quantitatively is not synonymous with the term *elastic* used qualitatively to describe a type of action. Elastic action denotes a cycle of loading and unloading without permanent set, whereas elasticity indicates the maximum degree of elastic action possible. Also the term

elasticity is not to be confused with modulus of elasticity.⁵

33. Stiffness.—Resistance to deformation caused by stress.

a. Modulus of elasticity or Young's modulus is the ratio of stress to strain within the proportional range in tension or compression. The modulus of elasticity is equal to the initial slope of the stress-strain diagram and is proportional to the initial slope of the load-deformation diagram of a tensile or compressive test or to the initial slope of a load-deflection diagram of a flexural test (see Art. 43).

b. Modulus of rigidity or modulus of elasticity in shear is the ratio of the unit shearing stress to the unit shearing strain below the proportional limit. It may be evaluated as the initial slope of the stress-strain diagram and is proportional to the initial slope of a torque-twist diagram.

c. Secant modulus of elasticity is the ratio of the unit stress to the unit strain above the proportional limit. It has little use in design as most structures and machine parts are designed to operate within the proportional range.

34. Resilience.—The resilience of a member or specimen is its capacity for storage of mechanical energy. Resilience is evaluated in inch-pounds of energy. The modulus of resilience, evaluated in inch-pounds per cubic inch, is defined as the maximum amount of mechanical energy that may be stored in a unit volume of the material under axial loading and be completely recovered upon the release of stress. It is numerically equal to the area under the elastic portion of a stress-strain diagram for a tensile or a compressive test. Normally the proportional limit is substituted for the elastic limit in which case the modulus of resilience is equal to $\frac{1}{2}S_e\epsilon$ or $S^2/2E$, where S = proportional limit, ϵ = elasticity, and E is Young's modulus. As indicated by the preceding definition, the modulus of resilience may be evaluated as the total energy content of a specimen at the proportional limit divided by its volume only when the stress is uniform throughout the volume.

By analogy the modulus of resilience in pure shear would be $S_s^2/2E_s$.⁶

⁵ Modulus of elasticity (literally, measure of elasticity) is not a measure of elasticity, but a measure of stiffness. Cold-rolled steel has a greater elasticity (0.002) than structural steel (0.001), but the two have the same modulus of elasticity (30,000,000 p.s.i.).

⁶ This requires that the shearing unit stress be constant throughout the volume under consideration, a condition which is approached in a thin-walled cylinder subjected to torsional stress (see Art. 54).

When the stress is not uniformly distributed, the modulus of resilience is greater than the average work per unit volume at the proportional limit. The maximum amount of energy per unit volume which can be stored in a solid circular member in torsion within the proportional range is $S_s^2/4E_s$ or one-half of the modulus of resilience in shear. For a rectangular beam with a concentrated load at the center the maximum amount of energy which can be stored within the proportional range is $S^2/18E$ or one-ninth of the modulus of resilience.

Resilience is the property that enables a material to withstand impact without permanent distortion. High elastic strength combined with high elasticity produces high resilience. Spring steel is resilient by virtue of its high elastic strength, in spite of its low elasticity, and rubber is resilient by virtue of its high elasticity, in spite of its relatively low strength.

35. Toughness.—Capacity for absorption of mechanical or strain energy up to failure (measured in inch-pounds of work or energy).

The modulus of toughness is measured by the average work of rupture per cubic inch of material and is determined from a tensile or compressive test as the area under the complete stress-strain diagram (inch-pounds per cubic inch). This area may be computed with the aid of a planimeter, by counting squares on the coordinate paper or by dividing the area into convenient geometrical figures.

For ductile materials that neck down prior to failure, the value obtained will depend in part upon the dimensions of the test specimen since the work performed beyond the ultimate strength is largely localized in the vicinity of the break. A short length of the specimen containing the break shows a higher modulus of toughness than the average for the whole specimen. Toughness is the property that offers resistance to fracture under impact and may be visualized as the opposite of brittleness or friability. Copper and mild steel exhibit toughness.

There is ample evidence to indicate that the response of a material to loading may be greatly influenced by the rate at which the load is applied. Material loaded rapidly will develop a different ultimate strength and percentage elongation than it would if loaded slowly. Hence the modulus of toughness, or area under the stress-strain diagram, may be dependent upon the rate of loading. Since an impact load is a load applied very rapidly, the

modulus of toughness as obtained from a slowly applied load may give an erroneous indication of the energy that can be absorbed under impact.

Various types of impact tests, such as the Charpy and the Izod, are employed to obtain coefficients which are more or less proportional to the toughness of a given piece of metal. While such coefficients are useful for comparative purposes, the results are not easily evaluated in terms of the fundamental property because of uncertainty regarding the distribution of the energy throughout the specimen. Impact is discussed further in Chap. X.

36. Hardness.—Hardness is variously defined as the capacity for resisting penetration, abrasion, etc. The measures of hardness are varied, and the property is generally expressed by a hardness coefficient which may or may not be susceptible of expression in rational units. A material may be quite hard according to one criterion and relatively soft according to another. The hardness as determined by the Brinell, Rockwell, and some other tests bears for some metals, especially the ferrous, a rather definite empirical relationship to the ultimate strength; hence a hardness test is sometimes employed to obtain an estimate of strength when an actual strength test is not feasible or desirable. Hardness is treated more fully in Chap. IX in connection with tests for its determination.

37. Endurance.—The capacity for withstanding repeated applications of load.

The endurance limit is defined as the highest stress (pounds per square inch) that can be applied millions of times without causing failure. The evaluation of the endurance limit requires special equipment and extensive testing over a period of time.

38. Poisson's Ratio.—The ratio of the unit deformation at right angles to the load to the unit deformation in the direction of the load within the elastic range of stress (a ratio, no units). Because a relatively small lateral deformation must be measured over a gage length which is usually short, sensitive measuring apparatus is necessary for the evaluation of this property. Poisson's ratio is rarely specified in acceptance tests, but it assumes importance in analysis of some of the more complicated stress situations such as those which involve biaxial and triaxial stresses.

39. Mechanical Hysteresis.—The energy absorbed by a material in a cycle of loading and unloading (inch-pounds per cubic inch). It may be evaluated from the stress-strain diagram as the

area between the loading and the unloading curves. Hysteresis indicates imperfect resilience just as set indicates imperfect elasticity.

SUPPLEMENTARY QUESTIONS

45. Name a measure and state the units used in this country for each of the following properties:
 - a. Elastic strength.
 - b. Ultimate strength in flexure.
 - c. Resilience.
 - d. Endurance.
 - e. Toughness.
 - f. Ductility.
 - g. Stiffness.
 - h. Elasticity.
 - i. Relative lateral deformability (elastic).
46. a. Explain the difference in units used for the strength of a member and those used for the material of which the member is composed.
 b. Make the corresponding comparison with respect to toughness.
47. Distinguish between
 - a. Stiffness and elasticity.
 - b. Resilience and toughness.
 - c. Yield point and ultimate strength.
 - d. Ductility and elasticity.
 - e. Modulus of rigidity, modulus of rupture, modulus of elasticity, and modulus of resilience.
 - f. Yield strength and yield point.
 - g. Elastic limit and proportional limit.
 - h. Hysteresis and work of rupture.
 - i. Stress and strain.
48. Why is it difficult to evaluate the elastic limit?
49. As measures of elastic strength, what are the relative advantages and disadvantages of each of the following:
 - a. Proportional limit.
 - b. Johnson's apparent elastic limit.
 - c. Yield point.
 - d. Yield strength.
50. Which of the following materials has a yield point:
 - a. Mild steel.
 - b. Cast iron.
 - c. Concrete.
 - d. Timber.
 - e. Hard steel (high-carbon steel).
51. a. Why should cold-worked steel not have a well-defined yield point?

- b. Does unannealed cold-drawn steel wire have a yield point? Why?

52. Are "stress" and "strain" properties of a material? Explain.

53. Indicate what is wrong or redundant in each of the following:

- a. Unit stress in pounds.
- b. Poisson's ratio is 0.20 in.
- c. The work of rupture of the material is 14,600 in.-lb.
- d. Young's modulus for steel is about 29,000,000 p.s.i. which indicates that its elasticity is high.
- e. Unit deformation in inches per inch.
- f. The ultimate percentage elongation is 23 per cent.
- g. The modulus of rupture is 800 lb.
- h. The total load carried by the member was 200,000 p.s.i.
- i. The material is brittle but very tough.
- j. The high resilience of the material shows it to be strong and ductile.
- k. The bar was strained to 40,000 p.s.i.
- l. The timber was stressed to its yield point.

54. In many countries metric units are used. One kilogram per square centimeter happens to be approximately equal to 1 atmosphere (14.70 p.s.i.), and this easily remembered fact is often useful for making rapid cross calculations where metric data are cited or used. Other conversion relationships are

1 lb. = 0.4536 kg.	1 kg. = 2.20 lb.
1 in. = 2.54 cm.	1 cm. = 0.394 in.
1 sq. in. = 6.45 sq. cm.	1 sq. cm. = 0.155 sq. in.
1 cu. in. = 16.35 c.c.	1 c.c. = 0.0612 cu. in.

- a. Verify the validity of the above-mentioned rule of thumb, and indicate the approximate percentage of error involved in its use.
- b. Express each of the following properties in appropriate corresponding metric units, indicating what the units are in each case:

- (1) Modulus of elasticity = 29,000,000 p.s.i.
- (2) Yield point = 41,000 p.s.i.
- (3) Modulus of resilience = 24 in.-lb. per cu. in.
- (4) Ultimate elongation = 26 per cent.
- (5) Poisson's ratio = 0.21.
- (6) Offset for yield strength of 0.2 per cent.
- (7) Modulus of rupture = 600 p.s.i.
- (8) Modulus of rigidity = 12,000,000 p.s.i.
- (9) Work of rupture = 15,000 in.-lb. per cu. in.
- (10) Total load = 20,000 lb.

55. How does the average amount of energy per unit volume stored in a shaft stressed to the proportional limit compare with the modulus of resilience of the material in shear if the shaft is

- a. Solid?
- b. Hollow, with a thin wall?

56. a. What value of Poisson's ratio would correspond to zero lateral strain?
- b. What value of Poisson's ratio would correspond to elastic deformation at constant volume?
- c. Between what limits must Poisson's ratio lie?
- d. Does Poisson's ratio closely approach these limiting values for any of the engineering materials? If so cite illustrations.
- e. Are values of the nonelastic equivalent of Poisson's ratio (stresses above the proportional limit) higher or lower than the valid elastic values for the same material?
- f. If the lateral strainometer fails to record all the deformation that occurs, how is the value found for Poisson's ratio influenced?

57. a. The modulus of elasticity of a wire cable is less than the modulus of elasticity of the metal wires of which the cable is composed. Explain.
- b. A used cable may be expected to be stiffer, *i.e.*, to have a higher modulus of elasticity, than a new cable. Why?

CHAPTER III

EVALUATION OF PROPERTIES FROM LOAD-DISPLACEMENT DATA

40. The Data.—The properties of materials are evaluated from data secured by test. An observation generally involves the measurement of a load and of a length. Observations are usually, but not necessarily, taken at some predetermined interval of load or of length.

Data secured by experiment always contain inaccuracies from such sources as lag, or other imperfect functioning of equipment, and from approximations involved in reading and recording values.

Because of the errors which are probably present in every experimental observation and because of the variability in the material, values of properties obtained from a single pair of observations may differ considerably from the average value.

Obviously, the average of duplicate observations is always more nearly correct than the least accurate of the observations averaged.

Further consideration, however, makes it apparent that the data should not all be accorded equal weight. Some observations may be positively "wild" and others relatively so. More refined methods of analysis of data have been developed by mathematicians. These are designed for the following purposes:

a. To determine the most probable values for the quantities which are represented by the data (essentially a process of weighted averaging).

b. To develop criteria for detecting "wild" observations (observations so far from the mean as to indicate the probability of mistakes in reading or recording). These should be discarded rather than averaged.

c. To predict the "probable deviation" (the error likely to be present in any one observation taken at random).

d. To determine correlation coefficients (numbers useful for judging the consistency of the data and for determining the validity of the trends shown).

The consideration of the recognized methods for judging and weighting data lies outside the scope of this course,¹ but in being advised that such methods exist, one needs also to keep clearly in

mind that no amount of mathematical adjustment will make good data out of poor data. Such adjustment may, however, prevent one from mistaking poor data for good data.

41. Diagrams.—In simple experimental work a diagram plotted from test observations gives a means of accomplishing, in an elementary manner, what could be accomplished with greater precision by statistical analysis. The width of the zone defined by the group of plotted points (the spread) gives an excellent conception of probable deviations from the mean (the mean being represented by the smooth curve or median line that best represents the group of points). Stray points located far from the mean are disregarded. If the points are scattered erratically and the trends are ill-defined, a lack of correlation or significant relationships between the variables is indicated. Thus on a diagram one does "by eye" that which would be done more exactly and laboriously by mathematical processes. Obviously a graph affords a rational evaluation and use of data that would be impossible to attain as readily without it. A carefully plotted graph becomes an adjunct to practically all problems that require the evaluation of any but the simplest of physical properties.

The properties described in the preceding chapter are with few exceptions either stresses or deformations, or else they are functions of stresses and deformations. Such properties as ultimate strength, yield point, and percentage elongation may be obtained directly from a single pair of observations. Other properties, such as proportional limit, yield strength, elasticity, and toughness, are dependent upon more than a single pair of observations for their evaluation. Some form of load-displacement diagram provides the most convenient method for their evaluation.

The simplest diagram for a test of a specimen under axial load is one in which the total loads are plotted against total strains. However, the conventional stress-strain diagram is much more useful

¹Among the many good treatises on the subject are: "Statistical Methods," G. W. Snedecor, Collegiate Press,

Inc., Ames, Iowa, 1937; Manual on Presentation of Data (Report of Committee), *Proc. A.S.T.M.*, Vol. 33, Part I, p. 451, 1933. Also *Proc. A.S.T.M.*, Vol. 35, Part I, pp. 1411, 1418, 1935.

because in it, the information secured from the test of a *specimen* has (within the conditions of the test) been generalized to apply to the *material* of which the specimen is made, rather than simply to a specimen of specific proportions. From a stress-strain diagram practically all the properties usually desired can be evaluated readily.

For torsional and flexural tests it is customary to plot torque-twist and load-deflection diagrams as may be noted in connection with these portions of the work.

42. Construction of the Diagram.—The lower portion of the stress-strain diagram for practically all engineering materials is, or is assumed to be, straight. In other words, there is a range of stress over which proportionality of stress and strain is assumed to exist. It is customary, in accordance with this assumption, to draw the straight line which best represents the plotted data within the proportional range as shown in Fig. 16. The origin of plotting has no more weight than any other pair of observations in the set since it is also experimentally determined. It should be disregarded in selecting the location for the tangent portion of the curve.

The tangent usually misses the origin. This is probably due mainly to lag in either the load-measuring or strain-measuring mechanism. In correcting for this (in order to determine correct simultaneous values for stress and strain), it is best to continue the line until it intersects the x -axis as shown.² Every point on the stress-strain curve will then indicate its correct value of stress but will need to have a strain of 0.0 added to all strains as read from the strain scale.

In drawing load-distortion diagrams, as in other graphical work, it is important to select scales that are easy to use, both in plotting and in reading values from the curve.

43. Evaluation of Properties.—The properties should be evaluated from the curve after it has been drawn with due regard for the relative importance of each point rather than from individual points which were plotted.

² This procedure is based on the assumption that the loads or stresses are correct and that the strains are in error. For testing machines which are within the A.S.T.M. tolerance for error, the loads indicated by the machine will be substantially correct, whereas there will practically always be some error in strains because of lag in the instrument, probably due mostly to play in bearings at the beginning of the test.

Such properties as ultimate strength and yield point, which are stresses, may then be read directly as ordinates if the diagram plotted is a stress-strain diagram, or may be calculated from the ordinates if load or torque is plotted instead of stress, by using the appropriate relationships between stress and load or torque.

Such properties as elasticity, which is a strain, may be determined directly as abscissas if unit strains are plotted in the x direction. Appropriate conversion factors must be used if quantities such as total strain or angle of twist, which are proportional to unit strain, are plotted. In every case the strain must be measured from the intersection of the curve with the x axis rather than from the origin used in plotting the test data.

The modulus of elasticity is evaluated from the straight-line portion of the diagram. The modulus, which is S/ϵ , is *equal* to the slope of the initial straight-line portion of a stress-strain diagram and is *proportional* to the slope of a load-deflection or torque-twist diagram. The proportionality factor may be found by expressing the stress and strain in terms of the quantities plotted. For example, in a torsion test where torque is plotted against twist

$$E_s = \frac{S_s}{\epsilon_s} = \frac{\frac{Tc}{J}}{\frac{c\theta}{L}} = \frac{TL}{\theta J} = \frac{T}{\theta} K = \text{slope times } K$$

In determining the modulus of elasticity from a beam test, it may be simpler to get an expression for E by solving the equation for the deflection. For example, if the beam carries a load at mid-span and increments of load and deflections have been observed and plotted, the proportionality factor may be computed as follows:

$$y = \frac{PL^3}{48EI}, \quad E = \frac{P}{y} \frac{L^3}{48I} = \frac{P}{y} K = \text{slope times } K$$

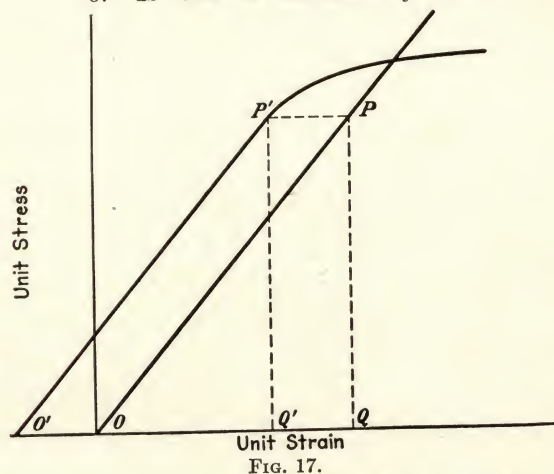
The numerical values of the properties which may be obtained from Fig. 16 are given so that the student can check his ability to evaluate properties from a graph.

SUPPLEMENTARY QUESTIONS

58. In accordance with the definitions of properties (Chap. II) Young's modulus E (modulus of elasticity so-called) can be expressed, for axial loading, as S/ϵ , where S is any stress below the proportional limit and ϵ is the corresponding strain.

- a. Evaluate E from Fig. 16 by selecting a point, as at A on the plotted curve, which corresponds to an even multiple of stress. Correct the corresponding strain by adding (in this case) the strain $O'O$ to that which is read along the x axis.
 - b. Make the same evaluation by referring to point B on the parallel straight line through the origin.
 - c. Repeat the evaluation using the parallel line, but select initially a strain which is an even multiple of 10, as for example that corresponding to point C .
59. In the preceding question
- a. Should the values secured be identical? Why?
 - b. If all three procedures are not equally simple, indicate your preference and also indicate which, if any, can be followed virtually without conscious calculation.
 - c. If the stress corresponding to point C happens to exceed the proportional limit (as at C' , for example) will the corresponding value for E be in error because of this?
 - d. Values corresponding to point D are convenient to use, but is D a good selection? Why?
60. a. From the table of data of a test a value of Young's modulus could be computed from a random selection of a stress (below the proportional limit) and its corresponding strain. With the aid of a sketch, point out the inaccuracy and uncertainty inherent in such a procedure.
- b. Would these uncertainties be removed if, instead of selecting random data, the average of all values below the proportional limit were used as the basis for the calculation? Explain.
- c. Point out clearly the fallacy involved in taking a point on the plotted mean curve (line $O'A$), as the basis for the calculation, without correcting it for the discrepancy $O'O$.
61. In Fig. 17 $O'P'$ represents a portion of a mean stress-strain diagram from plotted data.
- a. Show that area $OPQ = \text{area } O'P'Q'$.
 - b. If $S = \text{stress at proportional limit of the material}$, show that these areas each equal $S^2/2E$ and that this is the modulus of resilience.
 - c. A simple way to correct for $O'O$ in evaluat-

ing E and the modulus of resilience is to use the parallel line OP through the origin O . Is this a satisfactory method for



evaluating the elasticity as measured by the strain at the proportional limit?

62. In which of the following properties are the greater percentage errors introduced by failure to correct for the misplaced origin:
- a. Modulus of resilience.
 - b. Modulus of toughness.
 - c. Elasticity.
 - d. Ductility (as indicated by the percentage elongation).
63. Failure to correct for the origin introduces no error in values of proportional limit, yield point, ultimate strength, or rupture strength, but it does introduce error into values of Johnson's apparent elastic limit and the yield strength. Explain.
64. In Art. 43 it was shown that the expression for the modulus of rigidity of a circular shaft may take the form $E_s = \frac{T}{\theta} (K)$. In this form E_s or a multiple thereof may be read directly as the torque on a torque-twist diagram corresponding to some convenient multiple of θ .
- a. What value of θ should be selected for this purpose?
 - b. Show the details of how the method may be applied to evaluating E from a load-deflection diagram for a beam.
 - c. Can a similar method be used to evaluate E from the stress-strain diagram of a tensile or compressive specimen?
65. Is the use of a parallel straight line through the origin for correcting for the initial discrepancy as applicable to the torsional and flexural diagrams as to the stress-strain diagram?

CHAPTER IV

TENSILE TESTS

44. Use.—Tensile tests are employed commercially to obtain a measure of one or more of the following properties: (a) tensile elastic strength, (b) tensile ultimate strength, (c) ductility, and (d) toughness. Properties such as modulus of elasticity, Poisson's ratio, and modulus of resilience may be obtained if the measuring apparatus is sufficiently sensitive, but their evaluation is seldom required in routine commercial testing. They are

make certain that fracture occurs within the gage length selected.

The following table gives the dimensions of representative standard test specimens and indicates the variety of materials on which tensile tests are made.

46. Gripping Devices.—Ordinary wedge-shaped grips are satisfactory for commercial tests of bars of ductile material because the material is sufficiently ductile to deform plastically and thus adjust itself

TABLE II.—REPRESENTATIVE STANDARD TENSILE TEST SPECIMENS

Material	A.S.T.M. Designation	Description	Cross section		Gage length, in.
			Width, in.	Thickness, in.	
Metallic.....	E8-40T	{ Plate, shape, flat	$1\frac{1}{2}$	$t > \frac{3}{16}$	8
		{ Plate, shape, flat	$\frac{1}{2}$	$0.01 < t < \frac{1}{2}$	2
		{ Standard circular	$\frac{1}{2}$ in. diameter		2
		{ Wire or rod	Diameter $< \frac{1}{2}$ in.		10
Gray cast iron.....	A48-41	{ Small size	Nominal diameter		4 diam.
Cement.....	C77-40	Mortar briquet	0.505, 0.800, 1.25 diam.		Varies*
Gypsum.....	C26-40	Briquet	1	1	
Molded electrical insulation.....	D48-39	Briquet	1	$\frac{1}{8}$ or $\frac{1}{4}$	
Porcelain.....	D116-39		$1\frac{1}{8}$ diameter		1
Soft vulcanized rubber.....	D412-41		$\left\{ \begin{array}{l} \frac{1}{2} \\ \frac{1}{4} \\ \frac{1}{8} \end{array} \right.$	$\frac{1}{8}$ max.	2
				$\frac{1}{8}$ max.	2
				$\frac{1}{8}$ max.	1
Timber.....	D143-27	{ Perpendicular to grain	2	1	
		{ Parallel to grain	$\frac{5}{8}$	$\frac{5}{8}$	6

* At least equal to diameter of parallel portion.

usually required in the testing that accompanies research in engineering materials. The term *commercial test* is applied to tests performed primarily to check the quality of materials tendered as a basis for their acceptance or rejection.

45. Test Specimens.—The standard form of tensile test specimens varies with the nature of the material. Acceptance tests of ductile metals are usually performed on a length of the material if it is in the form of a rod or wire and on a strip if it is a sheet material. Brittle materials are usually formed into special shapes to permit the use of gripping devices which minimize bending and to

to some bending without lowering the ultimate resistance of the bar. A bar of ductile metal rarely fails either in or adjacent to the grips where complex states of stress and strain exist. On the other hand, a bar of brittle material invariably fails in or near the grips unless special precautions are taken to prevent crushing or shattering in the grips and to eliminate the bending due to imperfect alignment.

When a specimen is properly aligned, failure at the grips may be prevented by turning down the central portion or by providing it with enlarged ends. Reasonable freedom from bending may be

secured by the use of self-aligning linkages such as crossed knife-edges or spherical seated holders similar to those pictured for metal specimens in A.S.T.M. Designation E8-40T. The ends of the specimen are provided with a shoulder or are threaded for screwing into the grips. The reference also shows a gripping device for sheet materials. Thin specimens are especially difficult to test properly because of the tendency to fail progressively by tearing. Failure by tearing, which is a manifestation of nonuniform stress distribution, occurs to some extent in all tensile specimens. Other types of specimens and gripping devices are described in the A.S.T.M. Designations listed in the preceding article.

SUPPLEMENTARY QUESTIONS

66. What is the effect of improper gripping or poor alignment on the total load carried by a tensile specimen? Why?

67. Why does a specimen that is properly aligned and gripped give a more nearly correct indication

of the tensile strength of the material than does one which is not?

68. Which of the following self-aligning devices should offer the least frictional restraint and why:

- a. Crossed knife-edges.
- b. Spherical segment of $\frac{1}{2}$ -in. radius.
- c. Spherical segment of 1-in. radius.

69. a. Does initial curvature in a tensile test specimen tend to become greater or less as the test progresses?

b. Is the same true for a compressive specimen?

70. Explain clearly why initial straightness and good alignment of specimens are less important for ductile than for brittle materials.

71. a. Name some of the more important factors that need to be considered in selecting a gage length for use in tensile testing.

b. Considerable variation in gage length is shown in the tabulation of Art. 45. Are there any apparent reasons for this?

PROBLEM 4

Commercial¹ Tensile Test of Steel

A. Object.—To perform a commercial tensile test of steel and to evaluate some additional properties in the nonelastic range of stress.

B. Specimen.—A bar of steel. (These instructions assume that the bar is expected to meet the requirements of A.S.T.M. Designation A15-39 for billet-steel concrete-reinforcement bars.)

C. References.—Articles 24-31, 35, 40-43. A.S.T.M. Designations E8-40T and A15-39 or other appropriate designation.

D. Determinations to Be Made.¹

I. A.S.T.M. Requirements:

1. Yield point by drop of the beam, or halt of the dial.
 2. Tensile strength.
 3. Percentage elongation in 8 in.
 4. Ductility by the cold-bend test.
- ##### II. Additional Properties:
5. Yield point by dividers.
 6. Yield point by scaling.
 7. Rupture stress.
 8. Rupture stress based on final area.

9. Final elongation in each inch of gage length.

10. Percentage reduction of area.

11. Modulus of toughness.

12. Type of fracture.

13. Percentage elongation in two inches.

E. Procedure.

1. *Preparation of the Specimen.*—Take two micrometer measurements of diameter at right angles to each other near the mid-point of the bar. Record the readings with due regard for the accuracy with which they were taken. If the bar is deformed, determine its average area by weight (A.S.T.M. Designation A15-39, Sec. 10a). Lay off an 8-in. gage length symmetrical with respect to the length of the bar and correct to 0.01 in. Indicate the ends of the gage length by light punch marks on each side of the end marks. Also place single punch marks at each inch within the gage length and 1 in. outside of the gage length at each end.

2. *Performance of the Test.*—Place the specimen in the machine observing the cautions given in Art. 7. The grips may extend to within $\frac{1}{2}$ in. of the ends of the 8-in. gage length. The extra punch marks outside of the 8-in. gage length should be inside the grips to serve as reference points for

¹ Reference to such A.S.T.M. Designations as A15-39 indicates that only Items 1-4 are required in a commercial acceptance test. Items 5-13, while not required in a commercial acceptance test, supply basic information on the behavior of steel under tensile loading.

measuring the elongation in case the bar should break outside the gage length. Set the dividers for 0.04 in. more than the actual gage length indicated by the punch marks. Have the setup checked by the instructor. Apply load at the slowest speed. Keep the beam in balance at all times near the upper end of its vertical range of motion if the weighing system is of the lever type. Record the loads at the yield point as indicated by the elongation of 0.04 in., by the drop of the beam (or halt of the dial), and by scaling. Note at what section of the bar the scaling starts. Beyond the yield point take four readings of load and deformation at increments of 0.1 in., followed by increments of 0.3 in. until the specimen fails. Beyond the ultimate the load decreases rapidly so that care is required to balance the beam and to measure the deformation. Remove the broken halves from the machine, and observe the type of fracture. Measure the final length of each inch within the 8-in. gage length and the dimensions of the smallest cross section. Perform the cold-bend test with suitable equipment.²

F. Report.

1. *Graph Sheet.*—Construct a stress-strain diagram for the test, drawing a smooth curve to fit the plotted points. On the same sheet construct a graph with the elongation in each inch of gage length as ordinates and the number of the inch divisions as abscissas. Connect the plotted points with a series of straight lines since the points do not represent a continuous function. The axes for this graph may be set in from the border if desired.

2. *Results.*—Tabulate the limiting values of the physical properties specified in A.S.T.M. Designation A15-39 against the corresponding values obtained from the test.³ State whether or not you would certify the material as satisfactory on the basis of the tests performed. Indicate clearly all respects in which the specimen fails to meet requirements. Tabulate the other properties which were evaluated and compare them with available representative values. Explain, if possible, any apparent discrepancies or unusual results of the test.

² The bend test may be made on one of the pieces of the tensile specimen. This is a slightly more severe test than is specified because the ductility has been reduced by the strain-hardening during the tensile test. If such a specimen fails to pass the test, a retest should be made on an unstrained specimen.

³ If the bar did not break within the middle third of the gage length, see A.S.T.M. Designation E8-40T, Art. 24(c), for the proper evaluation of the percentage elongation.

G. Supplementary Questions.

72. The average cross-sectional area of a deformed bar is determined from its weight and its length.

- Is the strength obtained by using this area greater or less than that which would be obtained from a plain bar of the same material?
- Which properties have their values affected by any error or element of approximation inherent in this method of determining the area?
- Discuss the fairness of the method from the viewpoint of the manufacturer and of the purchaser.
- Can you suggest a fairer procedure?

73. a. If a nominal $\frac{1}{2}$ -in. square bar 20 in. long is weighed with an error of 1 oz., what is the percentage error in the area obtained for the bar? Steel weighs about 490 lb. per cu. ft.

- What would be the percentage error if an error of 1 g. were made in weighing the bar on a small metric balance?
- What are the corresponding percentages of error in the stresses obtained?
- What errors in measuring the length would produce the same errors in apparent cross section?
- For a fixed error in weight does the percentage error in area decrease or increase as the size of the bar is increased?
- Does a given error in measuring the length of bar produce the same or a different percentage of error in the cross-sectional areas of bars of different sizes?
- Many laboratories have platform scales of about 250-lb. capacity which are sensitive and accurate to about 0.01 lb. Assuming 0.02-lb. error in weight, what are the corresponding errors in the average areas of $\frac{1}{2}$ -in. and 1-in. square bars 20 in. long as determined by the weighing method?

74. a. Compare the stress in the bar at rupture as computed from the area at the break with the ultimate and rupture strengths obtained for the material.

- Why is not the actual area at the fractured section a suitable basis for defining strength?

75. Since the designer uses nominal (not actual) areas in proportioning the size of members why is

the ultimate strength based on the actual and not the nominal area?

76. Explain why the percentage elongation in 2 in. exceeds that in 8 in.

77. *a.* Why should an upper limit be set on the strength?

b. Should material that is sufficiently ductile but which overruns in strength be rejected?

78. *a.* Are the expressions for the determinations of minimum elongation rational or empirical?

b. Why is there no upper limit on the permissible percentage elongation?

79. *a.* Why should an upper limit be set in A.S.T.M. Designation A15-39 for phosphorus and none for sulphur? (See text-book on properties of materials.)

b. Why are there different limits for different manufacturing processes?

80. Why should the requirements for the cold-bend test and for the percentage elongation vary with the diameter of bars?

81. Name two other forms of bend tests and state their purpose briefly. (See A.S.T.M. Designation A41-36.)

82. *a.* Why does scaling of the specimen at the yield point usually start between the grips?

b. Did it in this test?

83. Can any conclusions be drawn regarding the possible effect of the punch marks on the strength of the bar at the punched sections?

84. *a.* Are wedge grips of the type used suitable for tests of brittle material?

b. What precautions are necessary to obtain satisfactory tensile tests of brittle materials? (A.S.T.M. Designation E8-40T.)

c. At what section along its length should a bar of brittle material be expected to fail?

d. At what section along its length should a bar of ductile material be expected to fail?

85. Can the elongation of a specimen be determined accurately by measuring the change in distance between the platen and the head of the testing machine? Why?

86. Why should a stress-strain diagram be preferable to a load-elongation diagram for presenting the results of this test?

87. *a.* What property of the material is represented by the area under the stress-strain diagram?

b. In what units is this property measured?

c. Make qualitative comparisons of mild steel, hard steel, and cast iron as regards this property.

d. Indicate the significance of this property.

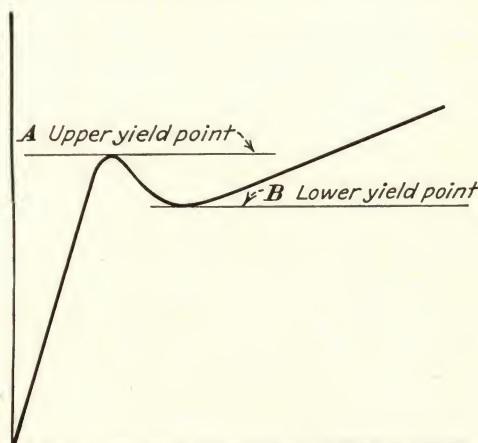


FIG. 18.—Upper and lower yield points (not to scale).

88. *a.* Was there a noticeable evolution of heat at any stage of the test?

b. Was it localized or general, and what did it signify?

89. *a.* Compute the approximate value for the modulus of toughness for the inch in which the fracture occurred; compare this value with that for the specimen as a whole.

b. What area is used for evaluating the modulus of toughness?

c. Since the modulus of toughness in a compressive test is taken as the area under the stress-strain diagram to the ultimate, might it not also be proper to do the same in tension instead of taking the area under the entire stress-strain diagram?

90. The rupture load is less than the ultimate load in a tensile test of a ductile material. If the load had been hung from the specimen,

a. Would there have been any apparent distinction between ultimate load and rupture load?

b. How might such a condition be simulated in a tensile test?

91. *a.* Does a structure always fail when the ultimate strength of a ductile element of it is reached?

b. How might the situation differ between elements consisting of a link in a chain and one strand of wire in a cable?

- c. Which element corresponds to the method of test which you used and which to that outlined in Question 90b?
- d. Is either case typical of conditions usually met in practice?

92. As usually conducted, a tensile test of a ductile bar shows an upper and a lower yield point (*A* and *B* of Fig. 18).

- a. What is the probable explanation for this phenomenon?
- b. Which should be the better criterion of elastic strength?
- c. Which is the simpler one to evaluate in a commercial test?
- d. Which would you expect the manufacturer to prefer and why?

PROBLEM 5

Tensile Test of Metal in Elastic Range

A. Object.—To determine tensile properties of a metal in the elastic⁴ range of stress.

B. Specimen.—Metal bar.

C. Special Apparatus.—Extensometer.

D. References.—Articles 10, 28, 32–34, 39. A.S.T.M. Designation E8-40T.

E. Determinations to Be Made.

1. Elastic strength.
 - a. Proportional limit.
 - b. Johnson's apparent elastic limit.
 - c. Yield point.
 - d. Yield strength for an offset of 0.2 per cent.
2. Modulus of elasticity.
3. Modulus of resilience.
4. Hysteresis.
5. Elasticity.

F. Procedure.

1. *Preparation for the Test.*—Determine the mean diameter of the specimen from two micrometer readings taken at right angles to one another near the center of the gage length. From careful measurements with a steel scale determine the multiplication ratio of the extensometer. Calculate the increments of extensometer reading which will give approximately 10 observations below the probable proportional limit or other unit stress designated by the instructor. Place the specimen in the machine and attach the extensometer firmly by hand. Do not use wrench or pliers to tighten thumbscrews. Loosen or remove the spacing bars and set the measuring device of the extensometer so that it will indicate throughout the range of deformation expected. Have the setup checked by the instructor.

2. *Performance of the Test.*—Record the initial reading of the load and the initial reading of the extensometer. Apply load at the slowest testing speed, and take observations at the selected incre-

ments of strain without stopping the machine.⁵ Continue the observations above the proportional limit to define the curve for a sufficient distance to permit a yield-strength determination. When the designated maximum stress or deformation is reached, release the load slowly, and take five readings of load and deformation to indicate the unloading curve. Remove the extensometer and take the bar out of the machine.

G. Report.

1. *Graph Sheet.*—Construct a stress-strain diagram for increasing and decreasing loads. Indicate the properties on the curve wherever possible.

2. *Results.*—Tabulate the values of the properties determined and compare these with such values as are available in textbooks on materials.

H. Supplementary Questions.

93. a. Distinguish clearly between proportional limit and elastic limit.
- b. Could the elastic limit have been determined without drastically altering the testing procedure? Explain.
94. a. What are the advantages of Johnson's apparent elastic limit?
- b. Is it a more or a less definite quantity than the proportional limit?
- c. For a given bar, which of these two properties is always represented by the higher unit stress?
95. a. Distinguish between yield strength and yield point.
- b. Which of the two properties has the wider range of applicability?
- c. Does spring steel have a yield point?
- d. Does spring steel have a yield strength?
96. a. In this test which properties, if any, of the material were probably altered? How? Why?

⁴ Including the properties on the boundary between the elastic and plastic ranges.

⁵ If the test is performed by a two-man squad, it may be desirable to operate the machine by hand and stop for each set of readings.

- b. Is there any range of stress which can be applied to the material without appreciably altering the values of some of its properties? Explain.
 - c. Why upon each successive loading above the former yield point, is the new yield point less pronounced?
 - d. Why does not hot working decrease the ductility?
 - e. Why does annealing to above the critical range relieve overstrain?
 - f. Does cold working affect all parts of the cross section alike?
97. What properties are measured or indicated by
- a. Modulus of elasticity?
 - b. Modulus of resilience?
 - c. Hysteresis?
98. Compare modulus of resilience with modulus of toughness on the basis of
- a. What they indicate.
 - b. The units in which they are expressed.
 - c. Practical uses for which high values are desirable.
99. a. If the modulus of elasticity of one material is greater than that of another, does it follow that it also has a higher elasticity? Illustrate answer by citing a pair of representative materials.
- b. Give the approximate range of the tensile modulus of elasticity for steel. What is a good value for an average approximation that will rarely be more than 5 or 6 per cent in error?
- c. In general, the alloys of steel have about the same modulus of elasticity as structural steel. Name one or two notable exceptions.
100. a. Poisson's ratio was not evaluated. What additional measurement or measurements should have been taken to determine it?
- b. In what units is it expressed?
- c. Is it limited to the proportional range of stress? Why?
- d. What is a reasonable value of Poisson's ratio for steel?
- e. What are reasonable values of Poisson's ratio for other engineering materials?
101. With continuous-reading or self-indicating strainometers and testing equipment, stress-strain data can be taken "on the run." With other types of strainometers load must be applied in successive increments with stops for readings of load and deformation. Under the second method the load usually drops off slightly while preparations are being made for a reading, and the poise is either backed up a little or load is applied to bring the beam back to balance as the readings are taken.⁶
- a. What should be the nature of the difference between stress-strain diagrams obtained by the two methods?
 - b. Should the differences be more pronounced in the early or in the later stages of the test?
 - c. Why does the beam drop when application of load is interrupted?
102. a. What produces the condition known as "overstrain"?
- b. What constitutes a state of overstrain?
- c. What is the term applied to overstrain which is part of the manufacturing process?
- d. Name three commercial products in which overstraining is a part of the manufacturing process.

⁶ An alternative would be to read the indicated deformation and load without again bringing the beam to balance.

CHAPTER V

COMPRESSIVE TESTS

47. Use.—Compressive tests are commonly used as a basis for acceptance of such materials as concrete, timber, tile, brick, and stone. They are seldom specified for metals since tensile and, in a few cases, flexural tests supply essential information more easily. In a compressive acceptance test the ultimate strength is usually the only property observed. The specifications devote particular attention to the selection of the samples, the types of specimens, and the technique of testing.¹ Compressive tests, like other tests, are also employed in research to determine mechanical properties and characteristics of materials under load.

48. Test Specimens.

a. Size.—The size of a test specimen is determined by such factors as the texture and uniformity of the material and the gage length required. Otherwise, the smaller the specimen, the better, since the cost of fabricating, transporting, storing, and testing increases with size.

The specimen must, however, be sufficiently large to constitute a representative sample of the material. Metal, for example, is fine textured, and a relatively small volume may, under certain conditions, properly represent a member or a heat. A larger concrete specimen will necessarily be used with larger sizes of aggregate. Otherwise, individual fragments of aggregate might produce erratic test results not representative of average material.² To represent average material properly, a specimen of timber containing small knots, irregularities of grain, and other minor defects would need to be much larger than a specimen from a clear, uniform piece.

The A.S.T.M. (Designation E9-33T) specifies three lengths of metal specimen. The three lengths may be used with equal facility if only the compressive strength is desired, but the longest speci-

men is generally the most convenient where strains are to be measured.³

b. Form.—Compressive specimens are generally prismatic or cylindrical. The ratio of the height to the diameter or to the least lateral dimension (h/d) should be between 2 and 10. Within these limits experience shows that specimens of a given material may be expected to show virtually the same compressive strengths and other properties.

For ratios below 2 the apparent strength of the material is increased by the effects of end restraint. For ratios above about 10 the stress condition is complicated by the presence of column action (bending) and the apparent compressive strength is decreased.³

The proportions of some of the standard compressive specimens are given in Table III.

TABLE III.—REPRESENTATIVE STANDARD COMPRESSIVE TEST SPECIMENS

Material	A.S.T.M. Designation	Type of specimen	h/d	h , in.
Brick.....	C67-41	Half brick (flat)	0.6	2½
Concrete.....	C39-39	Cylinder	2.0	Varies
Metal.....	E9-33T	{ Rod (short)	0.9	1
		{ Rod (medium)	3.0	2½, 3, or 3½
		{ Rod (long)	8.0	12½
Stone.....		Cube	1.0	—
Timber (longitudinal)	{ D198-27	Prism	4.0	24
	{ D143-27	Prism	4.0	8
	{ D143-27	Cylinder	5.5	9
Tile.....	C112-36	Full size	Varies	Varies

Note that not one of the specimens listed has an h/d ratio greater than eight, but that several of them have ratios below two. This departure from desirable practice is not necessarily serious from the standpoint of acceptance tests if all comparisons are to be of specimens of the same proportions and

³ In careful testing there is some evidence that values of yield strength are influenced slightly as the length is increased beyond the minimum necessary to avoid undue end effects. Sometimes, therefore, strain measurements need to be taken on a short gage length. For example, it is possible to secure stress-strain data with a 2-in. gage length on a specimen 2 in. in diameter and 4 in. long or with a 1-in. gage length on a specimen ¾ in. in diameter and 1½ in. long.

¹ See, for example, A.S.T.M. Designation C39-39, "Standard Methods of Making Compressive Tests of Concrete."

² Established practice usually requires a least lateral dimension of specimen not less than three or four times the diameter of the largest size of aggregate used. A.S.T.M. Designation C39-39 permits the use of 6-in. by 12-in. cylinders for aggregate up to 2 in.

the purchase specification has been prepared for that type of specimen. For example, half brick tested flat give strengths considerably above those for the same brick tested on edge or on end, but the results from different half bricks tested flat should give reasonably correct indications of their relative strengths.

The standard specimen for concrete has an h/d ratio of two, while drilled cores from pavements have varying ratios depending upon the ratio of the thickness of the pavement to the diameter of the drill. The following empirical reduction factors (A.S.T.M. Designation C42-39) are used to reduce the results of such tests to what they would probably have been for specimens of the standard geometric proportions. While these factors come from tests on concrete, they can probably, without serious error, be assumed applicable to materials in general.

h/d	1.75	1.50	1.25	1.10	1.00	0.75	0.50
Factor	0.98	0.97	0.94	0.90	0.85	0.70	0.50

The factor is the value by which the observed ultimate strength is to be multiplied in order to obtain a compressive strength comparable to that of a specimen with $h/d = 2.0$.

The table of standard compressive specimens indicates that simplicity, ready availability, or ease of fabrication is frequently the determining factor in the choice of test specimen to be used. For example, whole tiles and portions of individual bricks are used for compressive tests of these materials.

49. Loading Requirements.—Great care is required in compressive testing to insure proper transfer of load from testing machine to specimen. The load must be axial and applied uniformly over the ends of the specimen.

50. Methods for Obtaining a Satisfactory Transfer of Load between Testing Machine and Specimen.

a. Direct Method.

1. **GROUTING IN PLACE.**—Proper transfer of load may be secured by interposing, while plastic, a thin layer of quick-hardening material between the specimen and the testing faces of the machine. The material is allowed to harden under a slight load, and the specimen is tested in place. The layer should be only thick enough to fill the irregularities in the end of the specimen. If the layer is thicker than necessary, the test results are likely to be influenced by flow or yielding of the filler

material. Melted sulphur, alone or mixed with clay, and plaster of paris make good fillers.

Plaster of paris has been widely used as a grout in testing stone, brick, tile, and concrete. The hardened plaster is usually weaker than the material being tested, and recent tests have shown that concrete specimens capped with plaster of paris give considerably lower strengths than do companion specimens capped with some of the harder materials. Plaster of paris has the advantage over other grouting materials of availability and ease of application, but it is untidy to use and promotes rust on all ferrous surfaces with which it comes in contact, thus adding to the difficulty of maintaining trowels, pans, bearing plates, and other testing equipment. All contact surfaces of absorbent specimens which are to be tested dry should be protected by a coating of shellac or waxed paper,⁴ when plaster or other wet-mixed plastic is used as filler or cap material.

The grouting method is slow, and, while it generally produces a satisfactory transfer of load, it should be used only under more or less unavoidable circumstances.

2. **BEDMENTS.**⁵—Bedments, such as heavy building paper, beaverboard, Celotex, sheet lead, sheet rubber, steel shot and sand have been used to perform the function of a grout. Bedments differ greatly in effectiveness, but even the best of them do not insure a satisfactory transfer of load. Practically all bedments flow laterally as the test progresses. This is undesirable because its effect on the result of the test is indeterminate. Moreover the bedment near the center cannot "escape" to the same extent as that near the edges. This produces the equivalent of an end convexity or hard spot which functions more or less as a central wedge. When only one end of the specimen requires attention, as is the case for concrete cast against a plane metal base plate, the uneven end may be placed in a shallow pan or bottomless box of sand through which the load passes. The sand adjusts itself readily to the end irregularities, but the tendency of the sand to flow near the boundary punishes the edges of the specimen unduly, and the ultimate load carried is reduced because of this

⁴ Dry concrete, brick, tile, many stones, or any other fine-pored material have a strong affinity for moisture, the presence of which may have a pronounced influence on the strength obtained by test.

⁵ The use of bedments is prohibited in most specifications.

and the other factors common to bedments in general.

"Shot capping" constitutes a variation of "sand capping." Small hardened-steel shot are used in a manner similar to the sand. The shot distribute the load and fit the end irregularities, as does the sand, but can be used repeatedly, whereas the sand particles are broken and pulverized. After a few tests the fractured sand grains become fine enough to pack under the pressure. The shot capping constitutes a definite advance in the technique, although it probably is not the equivalent of grouting or good plastic capping. Special equipment for shot capping is commercially available.

b. Indirect or Alternative Methods.—Fortunately in most compressive testing a satisfactory transfer of load can be accomplished without recourse to grouting. To produce such a transfer, attention must be focused upon each of several important details.

1. The loaded faces should be normal to the geometric axis of the specimen.

2. The loading faces of the machine must bear uniformly against the specimen.

3. The resultant load must coincide with the geometric axis of the specimen.

The first condition must be met as a step in the preparation of the specimen. Whether cast, sawed, machined, capped, or ground, the ends need to be finished square across the section.

Plane contact surfaces for specimen and bearing plates constitute about the only practicable means for producing surfaces that can be brought to contact with the loading faces of the machine throughout. Moreover, experience has demonstrated that specimens with plane ends bearing against plane metal plates develop strengths comparable to those from specimens properly grouted into position.

Plane ends may be produced on metal specimens by grinding or machining. The bearing faces of concrete and stone specimens are sometimes ground also, but expense, time, and the special equipment required frequently limit the use of grinding for materials other than metals. The usual procedure for obtaining plane ends on nonmetallic specimens is to cap them with a plastic mixture which is permitted to harden against plate glass or machined metal plates. This procedure is similar to the grouting operation described previously except that the specimen is not placed in the testing machine at the time the cap is applied. Plaster of

paris, leadite, and melted sulphur, alone or mixed with iron filings or clay, are used as capping materials when the test is to be performed soon after capping. When the time is available for hardening, either ordinary portland or high early strength cement may be used.

Brick, tile, stone, concrete blocks, and drilled cores require capping on both bearing faces. Concrete cylinders are normally cast against a machined metal base plate, and only the top (as cast) needs to be grouted, ground, or capped. Mortar cubes are normally cast in molds with plane lateral faces, two of which can be used as bearing surfaces, thereby eliminating a need for capping. At present, side-cast prisms of height twice the lateral dimension are receiving experimental attention for possible adoption as compressive specimens for mortars and concretes. They would not require special end treatment.⁶

Sawed- or planed-timber specimens can adjust themselves to the bearing plates by local yielding that does not seriously disturb the uniformity of stress distribution.

Obviously the loading plane of the machine must coincide with the end of the specimen. These two plane surfaces coincide only if their aspects are the same. Parallelism between the loading faces of the specimen and the bearing plates of the testing machine is obtained by interposing a spherical bearing block that permits the loading plate to tilt slightly. One block is sufficient, since the entire adjustment can be made at one end of the specimen as well as, and even better than, at two.

The function of the spherical bearing block is to bring the planes of the block and specimens into coincidence as the test starts rather than to provide successive tilting adjustment in case the specimen yields unequally as the test progresses.⁷

The spherical bearing block serves to center the load, and it is important, therefore, that the speci-

⁶ Gilkey, H. J., and H. W. Leavitt. Comparisons of Different Types of Specimens for Compression Tests of Mortar, *Proc. A.S.T.M.*, Vol. 35, Part I, p. 281, 1935. Also Leavitt, H. W., and H. A. Pratt. A Statistical Analysis of Compression Tests on Mortar Cylinders, Cubes and Prisms, *Proc. A.S.T.M.*, Vol. 39, p. 851, 1939.

⁷ If successive adjustment were desired, crossed knife-edges would be preferable to a spherical segment since they develop very little frictional resistance under load. Although spherical bearing blocks are, or should be, well lubricated to permit easy initial adjustment, they develop high frictional resistance under load and are virtually locked after the beginning of the test.

men be accurately aligned with respect to the block.⁸

A spherical bearing block should have a radius of curvature approximately equal to the radius of the specimen and should be so placed that the center of the sphere coincides with the centroid of the adjacent face of the specimen. The block should be located above a vertically tested specimen, otherwise there will be some difficulty in bringing the upper head of the machine to a uniform bearing on the upper face of the specimen.

SUPPLEMENTARY QUESTIONS

103. Compare compressive testing with tensile testing in the following respects:

- a. Form and size of specimen that may be used.
- b. Capacity of testing machine required for material of a given strength.
- c. Lack of straightness, homogeneity, and initial alignment of specimen.
- d. Requirements for a proper transfer of load from testing machine to specimen.

104. a. What is the function of the spherical bearing block?

- b. Where should the center of the sphere be located with respect to the adjacent face of the specimen?
- c. Why?
- d. Why is it important that the block be above the specimen?

105. Is accurate centering of a specimen in the testing machine important

- a. When the load is applied through crossed knife-edges?
- b. When a spherical bearing block is used?
- c. When the specimen is grouted in place between nontilting platens?

106. The function of the spherical bearing block is primarily to make the plane of the load agree with the plane of the specimen as a test starts. With the load on the specimen, the block loses much of its capacity for further adjustment because of the friction developed.

⁸ If it were certain that the block would remain fixed against any further adjustment during the test, centering under it would not be essential. A load can be eccentric only as it is able to follow up an advantage from unequal yielding of the specimen. The axis of load on a specimen that is compressed between nontilting planes coincides with the axis of resistance of the specimen, regardless of its location laterally between the planes. Nevertheless, good testing practice dictates that all specimens be centered accurately.

a. Will inability of the block to tilt further as the test progresses tend to increase or decrease the effect of an initial eccentricity?

b. Will it tend to make the specimen support more load or less load than it would were the block free to "follow up" or vary its aspect with unequal yielding in the specimen as would be the case if crossed knife-edges were used?

c. Explain.

107. a. Demonstrate that for maximum stresses within the proportional limit of the material an eccentric load free to follow down (as when applied through crossed knife-edges) will double the intensity of compressive stress along one lateral face of a prismatic specimen of rectangular cross section if the eccentricity is one-sixth the lateral dimension.

b. On which face will this maximum compression occur?

c. What should the stress be on the opposite face?

d. How should the total load that the specimen can support at a given maximum elastic stress compare with what it could support if the load were centered?

e. What effects would still greater eccentricity produce?

f. Would eccentricity under tensile loading produce comparable results?

g. After the intensity of stress at the most stressed face exceeds the proportional limit, does the same distribution exist?

h. Should the ultimate load be more or less than half that which the well-centered specimen would support?

108. What eccentricity for a cylindrical specimen would produce a stress situation similar to that of Question 107a?

109. A compressive specimen has an end which is not plane.

a. Will the use of a spherical bearing block correct the difficulty?

b. If not, outline two procedures for producing a plane end so that a representative indication of the compressive strength may be obtained.

c. Is it good testing practice to use bed-ments such as beaverboard, sheet lead, or a sand bearing?

d. Why?

110. Various factors may contribute to error in the apparent compressive strength of a material as obtained by test: the end of the specimen may not be plane; the specimen may not be homogeneous laterally; it may be crooked or curved; the planes of the load may not be parallel to the ends of the specimen; or the specimen may be poorly placed under a spherical bearing block.

- a. If two or more of these objectionable conditions are present, is there a possibility of compensation, *i.e.*, could the error from one of them tend to be offset by the error from another, or is the resulting error always cumulative?
- b. Do such errors make the material appear to be stronger or weaker than it actually is?

111. In structures the loads on compressive members are rarely centered and loading conditions will, at best, be less closely controlled than they are in a well-conducted laboratory test. Should not the laboratory attempt to simulate practical conditions instead of taking every precaution to eliminate stray or uncontrolled variables? Explain.

112. A beam is supported by two posts. A load located at mid-span of the beam appears to be very eccentric, with respect to the supporting posts. Does it actually produce eccentric loading on the posts

- a. If the ends of the beam rest on centrally placed transverse pins?

- b. If the beam rests directly on the flat tops of the posts but is not rigidly attached to them?

- c. If the beam is rigidly attached to the tops of the posts?

113. Spherical bearing blocks are sometimes used at both ends of a specimen. Is this a needed or a desirable practice? Why?

114. From A.S.T.M. Designation C42-39 a table of correction factors has been given for correcting the test strengths obtained from concrete specimens having height-diameter (h/d) ratios below two.

- a. Do you judge these factors to be rational or empirical in their origin?
- b. Should they be applicable to similar specimens of material other than concrete?

115. Referring to the tabulation of some of the standard or more commonly used compressive specimens, indicate which, if any, of these are

- a. Too slender to give proper values of compressive strength.
- b. Too stocky to give proper values of compressive strength.

If some of the proportions fall outside of the desirable ranges is there any apparent justification for it?

116. If a standard test of a brick specimen indicates an ultimate compressive strength of 6000 p.s.i. and a standard test of a concrete specimen 3000 p.s.i., is it proper to say that the strength of that grade of brick is twice that of the concrete in question? Explain.

PROBLEM 6

Compressive Test

A. Object.—To perform a compressive test on an assigned specimen and to evaluate some of the mechanical properties of the material in compression.

B. Specimen.—Timber, portland-cement mortar, or concrete.

C. Special Apparatus.—Compressometer, and lateral extensometer (if Poisson's ratio is to be evaluated).

D. References.—Articles 41-50. A.S.T.M. Designation E9-33T.

E. Determinations to Be Made.

1. Elastic strength.
 - a. Proportional limit.
 - b. Johnson's apparent elastic limit.
 - c. Yield strength.

2. Modulus of elasticity.
3. Ultimate strength (if test extends to ultimate).
4. Ultimate unit deformation (if test extends to ultimate).
5. Poisson's ratio (if designated). *OUT*
6. Elasticity.
7. Modulus of resilience.
8. Modulus of toughness (if test extends to ultimate).

F. Procedure.

1. *Preparation for the Test.*—Take two right-angle measurements at mid-height with calipers and scale to determine the mean cross-sectional area of the specimen. Test the ends of the specimen on a bearing plate to see if they are plane. Consult the instructor if any deviation from plane-

ness is detected. Determine the multiplication ratio of the compressometer and the lateral extensometer, and compute increments of reading of strain such that about 10 points on the stress-strain diagram may be secured. Attach the compressometer and release the spacing bars. Turn the thumb-screw on the rod connecting the two yokes until the pointer on the dial micrometer moves, thus indicating that the instrument is ready for use. If Poisson's ratio is to be evaluated attach the lateral extensometer at mid-height on the specimen. Center the specimen beneath the spherical bearing block.

2. *Performance of the Test.*—Use the slowest testing speed or operate the machine by hand. Oscillate the spherical block slightly in a horizontal plane as it comes to bearing on the specimen. Take readings of loads and deformations simultaneously throughout the test. In case the test is not to failure, take readings of loads and deformations for decreasing as well as increasing loads. Sketch the failure if the specimen is broken.

G. Report.

1. *Graph Sheet.*—Construct a stress-strain diagram, showing all observed points. Distinguish between points for increasing load and decreasing load if failure was not reached. If lateral strains were measured, plot them from the same origin, using the same scale for stress and a scale four times as large for strain. Compute values of Poisson's

ratio (or its nonelastic equivalent) at appropriate intervals and plot them against stress near the right-hand side of the sheet. Indicate the required properties on the graph where possible.

2. *Results.*—Tabulate the properties obtained, noting the extent of agreement with values available from other sources.

H. Supplementary Questions.

117. Define hysteresis and show its relationship to a stress-strain diagram. If the specimen was not fractured and observations were taken of stress and strain with both increasing and decreasing loads, indicate whether or not there was any hysteresis.

118. Which should have the higher strength, a small clear specimen of timber or a full-size member?

119. Explain how a lack of homogeneity, such as a knot near one face of a timber specimen or differences in grain and stiffness, may produce the equivalent of eccentric loading.

120. a. Which of the properties listed can be evaluated without carrying a compressive test to failure?

b. Which of the properties are most important from the standpoint of the normal engineering use of materials?

121. Does the moisture content of this material have any significant effect upon the values of its properties?

CHAPTER VI

SHEARING AND TORSIONAL TESTS

51. Use.—Direct or cross-shearing tests are used frequently to determine the ultimate resistance of rivets and bolts and of timber parallel to the grain. Torsional shearing tests of metals are useful for evaluation of shearing elastic strengths, stiffness (modulus of rigidity, or modulus of elasticity in shear), and modulus of rupture or apparent ultimate shearing strength. Ultimate shearing tests of metals also give good indications of relative ductilities (by the amount of twist undergone), of relative toughness, and of uniformity as indicated by the spacing, distribution, and appearance of the lines of twist. Information on torsional stiffness can likewise be obtained from loading tests on helical springs, since torsion is the primary stress in such a spring under normal loading.

Neither torsional nor other shearing tests have been specified to any appreciable extent for acceptance purposes, and they are rarely so used.

52. Specimens.—A.S.T.M. Designation D143-27 specifies a shearing test for timber parallel to the grain and describes the standard specimen to be used. For metals, cross-shearing tests are usually made on rivets or other bars of circular cross section. Torsional tests of metals may be performed upon bars, usually of circular cross section, which may or may not have the central portion turned down to avoid breakage at or near the grips. There is little or no standardization in this field. Various kinds of torsional specimens have been used for research work with metals, concrete, and plaster. Tests on thin, hollow tubing have been used to evaluate true torsional properties beyond the proportional limit, since the torsional stress is nearly uniform over an area which is concentrated a given distance from the neutral point of the cross section.

53. Gripping and Measuring Devices.—Ductile materials tested in torsion may be held in a chuck with hardened serrated jaws. Brittle materials need a gripping device which will distribute the reaction more uniformly around the circumference of the specimen and which will not cause stresses sufficiently localized to result in failure in the grips under applied torsional loads.

Shearing deformations are measured in torsional tests by different forms of torsional strainometers or troptometers. Crude measurements can be obtained by noting the relative rotation of the grips, but much greater accuracy is required for the evaluation of torsional properties within the elastic range of stress. Various forms of troptometers are described in manufacturers' catalogues, several of which are listed among the references of Chap. I.

54. Properties.—Accurate evaluation of shearing properties is not possible from a cross-shearing test (such as a test on a rivet) for the following reasons:

- a. Cross shear cannot be applied free of bending.
- b. Cross-shearing stresses are not distributed uniformly over the cross section. Moreover, secondary compression and the bending alluded to above make it impossible to determine the true intensity of shearing stress at any point in the cross section.
- c. Unit-shearing deformations are indeterminate because of the shortness of the gage length required in order to minimize bending, and also because of local distortions from other causes.

Thus the only property obtainable from a cross-shearing test is the average intensity of stress at rupture and even this is not from shear alone. Bars, bolts, and rivets tested in single shear offer about half the resistance (or about the same resistance per unit of shearing area) as those tested in double shear.

Accurate determinations of elastic properties can be made from carefully conducted torsional tests, since torsion can be applied over a gage length which is remote from the grips and which can be kept free from bending. Total torsional resistance beyond the elastic limit can be measured, and a fictitious ultimate torsional strength, or modulus of rupture in torsion, can be computed from the ultimate load carried. The true values of yield point, ultimate strength, and toughness cannot be determined from solid specimens, as the material near the surface is more highly stressed than that near the center. Values for properties beyond the proportional limit can be approximated through

the use of thin, hollow specimens,¹ mentioned previously. Shearing tests of brittle materials, such as cast iron, concrete, and plaster result in spiral diagonal tension failures, since the shearing resistance exceeds that in tension.²

Reasonably accurate determinations of modulus of rigidity can be made from tests on helical springs; although flexure, cross shear, and some direct stress are always present. The relative importance of these varies with the proportions of the spring.

55. References on Shearing and Torsional Tests.

- a. Elementary textbooks on mechanics of materials, properties of materials, and laboratory manuals. Portions on shear, torsion, horizontal shear, shear in beams, riveted joints, helical springs, etc.
- b. Torsion of noncircular cross sections is treated in textbooks on advanced mechanics of materials. For example:
 - (1) Seely, F. B. "Advanced Mechanics of Materials," John Wiley & Sons, Inc., New York, 1932.
 - (2) Timoshenko, S. "Strength of Materials," Part I, D. Van Nostrand Company, Inc., New York, 1930.
- c. Shearing of timber.
 - (1) A.S.T.M. Designation D143-27.
 - (2) Luxford, R. F., and G. W. Trayer. "Wood Handbook," Forest Products Laboratory, U. S. Department of Agriculture, 1941.
- d. Torsional tests of concrete.
 - (1) Savage, J. L., I. E. Houk, H. J. Gilkey, and F. Vogt. "Engineering Foundation Arch Dam Investigation," Vol. II, pp. 454-455, Engineering Foundation, New York, 1934.
 - (2) Andersen, Paul. *Trans. Am. Soc. Civil Engrs.*, Vol. 100, Paper 1912, pp. 949-983, 1935. Equipment shown on pp. 955, 957, 977.
- e. Seely, F. B., and W. J. Putnam. Relation between Elastic Strengths of Steel in Tension, Compression and Shear, *Univ. Illinois Eng. Exp. Sta. Bull.* 115, 1919.
- f. Sauveur, A. The Torsion Test, Edward Marburg Lecture, *Proc. A.S.T.M.*, Vol. 38, Part II, p. 3, 1938. Also contains a bibliography.

SUPPLEMENTARY QUESTIONS

122. Distinguish between cross shear and torsional shear as regards

- a. The path of relative displacement for points in adjacent cross sections.

¹ Hollow torsional specimens to be tested beyond the yield strength should be turned down over only a short section in order to avoid failure by diagonal buckling due to the compressive stresses which are set up on diagonal planes.

² Since the failure actually occurs in tension, such torsional tests do not determine the ultimate shearing strength of the material, although they do indicate the maximum resistance which the member is able to offer under torsional loading.

- b. The portions of a circular cross section which are subjected to the maximum and minimum stresses.
- c. Measurement of strains and evaluation of such properties as elastic strength, modulus of rigidity, and modulus of resilience.

123. Under torsional stress ductile materials normally shear square across the section and many brittle materials have a spiral-shaped fracture similar to that displayed by a piece of chalk twisted to failure. Explain why.

124. a. Why does not the torsion formula supply correct values for the properties of a solid circular bar for stresses above the proportional limit of the material?

- b. Accurate values can be obtained from tests on thin-walled hollow shafts (provided that the thin-walled section is short enough to avoid failure by buckling rather than by shear). Why should this be true?

125. a. Should the apparent value (value computed from the torsion formula) of yield point, yield strength, and other stresses above the proportional limit as determined from the results of a torsional test on a solid circular bar be too high or too low? Why?

- b. How about the modulus of rupture or apparent ultimate strength?

126. a. Is the torsion formula applicable to bars of noncircular cross section?

- b. Should a square bar be stronger or weaker in torsion than a circular bar of the same material that could be inscribed in it?

- c. Which should be able to resist the greater torque—a round bar or a square bar of the same material and same area?

127. Large shafts, especially for ocean liners, are often made hollow. What is one possible explanation?

128. Does a shearing stress ever occur in one plane only? Explain.³

129. Can a true value of the ultimate shearing strength of a brittle material be obtained from a torsional test? Explain.

³ This question relates to matters generally considered in the treatment of shearing stresses in beams which in most textbooks are taken up subsequent to the study of torsion and riveted connections.

PROBLEM 7

Shearing Test of Rivet Steel

A. Object.—To perform a shearing test on mild steel.

B. Specimen.—A mild steel rivet, or short rod.

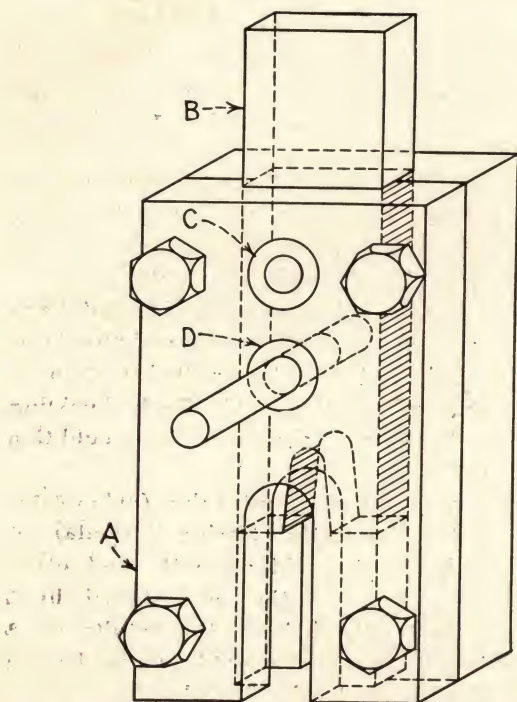


FIG. 19.—Diagram of a shear rig. Shows cutter in place for single-shear test on rod.

(A) Base (steel) made in two parts to facilitate manufacture and disassembly. (B) Cutter (hardened steel) contains hole for single shear and notch at bottom for double shear. (C) Hardened insert to support rivet in double shear. (D) Hardened insert (on one side only) to support rivet in single shear, other side slotted (not shown).

C. Special Apparatus.—Tackle for single shear and double shear (see Fig. 19).

D. Reference.—Articles 51–54.

E. Determinations to Be Made.

1. Average ultimate strength in single shear. 51,800 psi
2. Average ultimate strength in double shear. 48,900 psi

F. Procedure.

1. *Preparation for the Test.*—From the mean of two micrometer readings of diameter at right angles to one another, determine the cross-sectional area of the specimen at each of the sections to be sheared. If there is a ridge on the specimen, the measurements should be taken about 45 deg. from it. If the shear rig is adjustable, see that the plates fit snugly but do not bind. Adjust the rivet for testing in single shear, leaving one portion long enough to test later in double shear. Compute

the approximate ultimate load to be expected and check with the instructor before proceeding.

2. *Performance of the Test.*—Load at the slowest speed to the ultimate, which is indicated by an abrupt reduction in load. Record the ultimate load. Continue the test only far enough to sever the rivet completely. Repeat, testing the longer portion of the same specimen in double shear.

G. Report.—Tabulate the data, and compare the average unit shearing stress in single shear with that in double shear. Compare with values available from other sources. A 5000 psi

H. Supplementary Questions.

130. Would measurements of the relative movement of the plates of the shear tackle give accurate values of shearing deformation? Why?

131. a. From the results of the tests does the assumption commonly made in design of equal unit strength in single and double shear appear to be valid?

b. Is any reason apparent for a possible difference between strengths to be obtained in single shear and in double shear? If so, what is it?

c. Is any generalization on the relative strengths of the material in single and double shear justified on the basis of the evidence secured? Why?

132. To what stresses other than shear were the rivets subjected? Do the other stresses appear to be equally important in single and double shear?

133. Is shearing of the rivets the only manner in which a riveted connection may fail? Explain.

134. a. What tests for physical properties are specified in the A.S.T.M. specifications for rivets and rivet steel A141-39 and A31-40?

b. Is there any apparent reason why no shearing strength should have been specified in either case?

135. In what manner do the conditions for rivets in service differ from the conditions of the test?

136. In your estimation should the heating of rivets prior to use alter their structure and properties sufficiently to invalidate comparisons between them and the rivets which you tested? Explain.

137. Can a riveted joint be 100 per cent efficient (i.e., develop a resistance equal to that of the unpunched plate)?

- a. In shear?
- b. In bearing?
- c. In tension in the net section of the plate?
Explain.

138. Discuss the feasibility of using such a test as this one for obtaining the modulus of rigidity and other physical properties in shear.

139. a. What is the ratio of the maximum intensity of shearing stress to the average shearing stress over the cross section?

- b. Where in the cross section does the maximum intensity occur?

PROBLEM 8

Torsional Test of Steel

A. Object.—To evaluate some of the torsional properties of mild steel.

B. Specimen.—A mild steel rod.

C. Special Apparatus.—Tryptometer for measuring shearing strains.

D. References.—Articles 43, 51–54. Chapter on torsion in textbook on mechanics of materials.

E. Determinations to Be Made.

1. Elastic strength.
 - a. Proportional limit.
 - b. Johnson's apparent elastic limit.
 - c. Apparent yield point.
 - d. Apparent yield strength corresponding to an offset of 0.002 (0.2 per cent).
2. Modulus of rupture in torsion.
3. Modulus of rigidity.
4. Average amount of energy absorbed per unit volume at the proportional limit.
5. Average amount of energy absorbed per unit volume at the ultimate.
6. Hysteresis per unit of volume (if test does not extend to ultimate).
7. Elasticity.

F. Procedure.

1. *Preparation for the Test.*—Determine the diameter of the bar as the mean of two micrometer readings taken at about mid-length and normal to one another. Compute increments of tryptometer reading that will insure 10 observations of torque and strain within the elastic and, if the test is to be to the ultimate, 5 within the plastic range of stress. Care will be required to obtain observations defining the torque-twist curve in the vicinity of the yield point where there are relatively large increases in strain with little increase in torque. For estimating increments the proportional limit for the outside fibers may be assumed to be six-tenths of the proportional limit of similar material in tension, and the shearing modulus of rupture may be assumed to be equal to nine-tenths of the ultimate tensile strength.

Place the bar in the machine, attach the tryptom-

eter to give the desired gage length, and adjust it to insure proper readings along the arc or chord as the test proceeds. If necessary apply about 200 in.-lb. of torque to set the grips, after which the machine can be returned to initial balance by operating it backward.

2. *Performance of the Test.*—Twist bar slowly at a uniform rate. Take readings of torque and twist simultaneously without stopping the machine. When the yield point or other designated maximum loading has been reached, if the test is not to be carried to the ultimate, remove the load slowly, taking four readings of torque and twist to define the unloading curve. If the tryptometer is of a type subject to damage from overrunning, it should be loosened or removed before reaching the end of its range. After the yield point is passed, readings of angle change of the grips may be substituted for tryptometer readings, in which case the gage length may be assumed to be the free length of the bar between grips.

G. Report.

1. *Graph Sheet.*—If the test was carried to the ultimate, construct two curves from the same origin, one extending to the yield point and the other to the ultimate. Plot torques in inch-pounds as ordinates against total angles of twist in radians (in the gage length of the tryptometer) as abscissas.

2. *Results.*—Determine the numerical values of the properties, basing computations as far as possible on data taken from the graph. Tabulate the results, and compare the properties with available values from other sources. Also compare the values of torsional properties with the corresponding values obtained in the tensile test, indicating whether or not the steels used in the two tests were presumably of similar grades.

H. Supplementary Questions.

140. In a tensile test of ductile steel, failure occurs at a load well below the ultimate. Was that true for this test? Explain.

141. In the mechanics of materials the following relationship is derived:

$$E_s = \frac{E}{2(1 + m)},$$

where E_s = modulus of rigidity, E = Young's modulus in tension or compression, and m = Poisson's ratio. Compare the modulus of rigidity obtained by experiment with that given by this expression, using acceptable average values of Young's modulus and Poisson's ratio for steel.

142. Which of the properties evaluated in the test is the most necessary in spring steel? Why?

143. Shear may be either cross shear as in the case of a rivet or torsional shear as in this bar. In carefully conducted tests which type of shear

- Should have greater freedom from bending?
- Should permit more accurate measurements of shearing deformation?
- Should give better determinations of each of the properties evaluated in this experiment? State why.

144. A solid circular bar subjected to torsion has maximum stress in the outside fibers and zero stress at the center of the cross section.

- If the same bar is subjected to cross shear, what is the value of the maximum shearing stress, in terms of the average stress, and where is it located?⁴
- Indicate also the location and minimum value of the cross-shearing stress over the section.
- How is the variation of cross-shearing stress over the cross section taken into account
 - In the design of riveted connections? Why?⁴
 - In the design of beams? Why?⁴

145. Can the value determined in $E7$ properly be termed "the modulus of resilience in shear" for this material? Explain.

146. a. Can the value determined in $E5$ properly be termed "the modulus of toughness" for this material?

- Is the stress situation at the ultimate entirely analogous to the situation at the proportional limit? Explain.

⁴ These questions relate to matters generally considered in the treatment of shearing stress in beams which in most textbooks is taken up subsequent to the study of torsion and riveted connections.

PROBLEM 9

Test of Helical Spring

A. Object.—To observe the behavior of a helical spring under load and to determine some of the characteristics of the spring and the physical properties of the material of which it is composed.

B. Specimen.—Helical spring.

C. Reference.—Chapter on torsion and treatment of the helical spring in a textbook on mechanics of materials.

D. Determinations to Be Made.

- Modulus of the spring per turn, expressed in pounds per inch.⁵
- Modulus of rigidity of the material.
- Torsional shearing stress at maximum load.
- Average intensity of cross-shearing stress at maximum load.
- Energy stored in the spring per turn at maximum load.

⁵ Modulus of spring is load required to deflect spring elastically 1 in. Modulus of spring per turn (in pounds per inch) is load that would deflect one turn of the spring elastically 1 in. Thus for a spring of n turns, the modulus per turn is n times the modulus of the spring.

E. Procedure.

1. *Preparation for the Test.*—Determine the diameter of the bar forming the helix as the mean of two right-angle micrometer measurements. Incline the micrometer about 45 deg. with the axis of the helix to obtain the measurements. Determine the mean diameter of the helix from the diameter of the bar and either the outside or inside diameter of the helix. Select two gage points a whole number of turns apart between which the bar is of uniform section, and measure the distance between them. Compute the load that will produce a maximum torsional stress of 40,000 p.s.i. (or other designated stress) in the spring, and check this value with the instructor.

2. *Performance of the Test.*—Apply the load slowly in 10 approximately equal increments. Record load and distance between gage marks for each increment. Take observations for both increasing and decreasing load, starting back on a half increment of load in order to stagger observations. Make the final observation at zero load to

determine whether or not measurable set is present.

F. Report.

1. *Graph Sheet.*—Construct a load-deflection diagram with loads as ordinates. Distinguish between points for loading and unloading, but draw a single straight line as a mean for the entire zone of points.

2. *Results.*—Determine and tabulate the values of the properties required. State whether or not the modulus of rigidity obtained appears to be a reasonable one for the metal of the spring. Explain why the value obtained might be lower than that ordinarily given for steel (see Question 152).

G. Supplementary Questions.

147. Indicate which of the following properties can be evaluated from the data of this test, and state why. State units in which each property is expressed.

- a. Modulus of rigidity.
- b. Modulus of resilience.
- c. Proportional limit.
- d. Modulus of toughness.
- e. Modulus of the spring.

148. Convenient average values for the modulus of elasticity of steel in tension and torsion are 30,000,000 and 12,000,000 p.s.i., respectively. Compare the amount of energy which can be stored in a bar stressed in tension with that which can be stored in the same bar stressed in torsion.

- a. At equal stress which type of loading provides the larger reservoir of energy?
- b. How does the comparison for the maximum possible storage of energy stand if it is assumed that the proportional limit of steel in torsion is six-tenths that in tension?

149. Other types of springs function as flexural members. Judged from the reconnaissance of Question 148 should one expect a flexural spring to be as effective per pound of metal as a helical spring of similar material? Explain.

150. Energy can be stored by stressing axially, as is often done with rubber. Why is not metal commonly used for this type of energy storage?

151. a. If it were desired to obtain more accurate results by taking account of the bending and cross-shearing stresses, how might this be done?

- b. Which portions of the cross section are subjected to the greatest intensity of stress in each of these respects?

- c. Should the stress from cross shear add to the intensity of torsional shearing stress at the periphery? Why?

152. The measured deflections were due in part to cross shear and flexure. If that due to torsion only had been segregated, it is obvious that these deflections would have been somewhat smaller. Would the use of these lower values, instead of the total observed deflections, have raised or lowered the value obtained for the modulus of rigidity?

153. The calculations were made on the assumption that only torsional stresses were present. Does the fact that cross-shearing, flexural, and compressive stresses were neglected

- a. Make the maximum computed stresses lower or higher than the probable actual stresses?
- b. Give a result on the safe or unsafe side in selecting a proper limiting load to place on this spring?
- c. Give a value for modulus of rigidity which is higher or lower than the correct value for the material?
- d. Make the metal of the spring appear to be more stiff or less stiff than it really is?
- e. Affect the value found for the modulus of the spring? Why?
- f. Affect the value for the total energy that was stored in the spring? Explain.

154. If the spring had shown an appreciable set, would the maximum stress be greater or less than that given by the torsion formula? Explain.

155. Would it be possible to obtain good data by using the entire length of spring and measuring movement of the head of the testing machine as deflection

- a. If the metal were of uniform curvature and cross section over the entire length of the spring?
- b. If the metal were bent in, flattened out, or otherwise distorted near the ends? Point out several factors involved.

156. Did the diameter of the bar and the diameter of the helix need to be measured with the same precision? Why?

157. How did the total deformation at the periphery of the rod compare with the total deflection taken by the spring? What is the relationship between the magnitude of these two quantities?

158. One turn of the helix was assumed to be exactly $2\pi R$ in length. By a simple calculation show the extent of the approximation involved.

159. If the bar had been of noncircular cross section, would the formulas used in the determination of S_e and E_s be applicable? Why?

160. Helical springs are often valuable for use as essential parts of improvised testing machines, especially in research.

- a.* Explain with the aid of a sketch how a helical spring and an hydraulic jack could be used to apply and measure load in a compressive test. In a tensile test.
- b.* An arrangement is to be improvised for maintaining load on a compressive member for several months. A framework of three rods is provided for holding the load at any value desired. The spring has not been calibrated, but there is available a testing machine in which the assembly can be placed for loading and unloading. Explain how the load should be applied and what precaution should be taken at the completion of the test to determine whether or not the load had changed appreciably through deformation of the specimen, slack, or yielding of the spring or rods.
- c.* Describe a setup similar to that of *b* but where no testing machine is available. Spring has been or can be calibrated.

It may be desirable to vary or adjust the load occasionally during the test.

- d.* A car spring deflects 0.5 in. under a load of 5000 lb. applied to a specimen which is expected to acquire from creep an additional deformation of 0.03 in. during the loading period. Creep in the spring and framework is assumed negligible after the load has been applied. What reduction would the yielding in the specimen be expected to make in the applied load by the end of the loading period? What is the percentage of error introduced by the creep?

161. The movable head of a testing machine is not free to follow down and a very slight yielding of the specimen releases much of the load. How might helical springs be used to supplement the testing machine

- a.* In conducting a test simulating the condition for an isolated member supporting a load that could follow down to failure if the ultimate resistance were reached?⁶
- b.* In maintaining a constant load on a specimen in a testing machine for a period of hours or days?⁶

⁶ To avoid possibility of a serious accident, springs should always be so confined as to prevent more than a partial sudden release of stored energy in case of fracture or disturbance of the setup.

CHAPTER VII

FLEXURAL TESTS

56. Use.—Flexural acceptance tests may be specified for materials such as timber, concrete, cast iron, and clay products. In most cases the modulus of rupture is required, but other properties may also be evaluated.

Within the proportional limit, the flexural test is often useful for the ready determination of Young's modulus from the known load and the observed deflection. The value so determined is intermediate between the modulus of elasticity of the material in tension and that in compression, if the two differ. For most materials the difference is slight.

An indication of the relative stiffnesses of two materials above the proportional range may be obtained by comparing the deflection of geometrically identical specimens of the two materials when loaded in flexure. In a similar manner deflections and loads together give indications of relative toughness. An indication of the relative stiffness of two materials above the proportional range may also be obtained by measuring the deflections of geometrically similar specimens of the two materials and solving for the nonelastic equivalent of E in the expression for deflection.

57. Test Specimens.—Some of the standard test specimens are indicated in the following table:

TABLE IV.—REPRESENTATIVE STANDARD FLEXURAL TEST SPECIMENS

Material	A.S.T.M. Designation	Cross Section, in.		Span, in.	Loading
		Width or diam.	Depth		
Brick.....	C67-41	3½	2½	7	Mid-span
Cast iron.....	A48-41	0.875 1.20 2.00	.. .. ..	12 18 24	Mid-span
Concrete.....	C78-39	6	6	18	Third-points
Molded insulating material	D48-39	½	½	4	Mid-span
Timber.....	D143-27 D198-27	2 Structural sizes	2	28 180	Mid-span Third-points
Roofing slate.....	C120-31	4	..	10	Mid-span
Structural or electrical slate	C120-31	1½	1	10	Mid-span

A properly designed flexural test specimen will be of such dimensions that failure will occur by bending (tension or compression in extreme fibers) and not by horizontal or vertical shear or the diagonal stress that results from shear. For a rectangular beam loaded at the center of a single span, this will

be approximated when $L \geq \frac{d}{2} \frac{S_r}{S_s}$, where L = span length, d = depth of beam, S_r = modulus of rupture, and S_s = ultimate shearing unit stress.

58. Supports.—For acceptance tests, most specifications indicate the nature of the supports, which are usually rounded metal blocks. For testing nonmetallic materials, such as timber or concrete, small plates may be inserted between specimen and bearing blocks to distribute the load, thereby preventing local damage at points of concentration. Supports may both be rigid, both on rockers, or one rigid and the other free-swinging. The last arrangement is generally the best one, providing there is the equivalent of lateral rocker adjustment at one end, as it provides fair stability, combined with adjustability for change in length as the beam deflects, and also insures freedom from twist.

59. Loading.—Tests are generally made either with center loading or with two loads usually placed at either the third-points or the quarter-points of the span. The two-point symmetrical loading, wherever placed, has the advantage of giving a region of pure bending (constant moment and zero shear) between the loads, which is desirable for many tests.

Under two-point symmetrical loading a simply supported beam of rectangular cross section should be about equally resistant to failure by bending and

by shear when $aL = \frac{d}{4} \frac{S_r}{S_s}$, in which aL is the distance from either support to the nearer load. When $a = 0.5$ the expression reduces to that given in Art. 57. For a beam of circular cross section

$$aL = \frac{d}{6} \frac{S_r}{S_s}$$

60. Deflections.—When deflections are to be measured, care is necessary to insure that they are

referred to a datum that does not settle or change elevation with respect to the initial neutral surface as the beam is loaded. Care must also be exercised that local crushing at the load points or supports is not measured as deflection.

61. References on Flexural Testing.

a. A.S.T.M. Designations C67-41, C78-39, A48-41, D48-39, D143-27, D198-27, C120-31.

b. Stresses in beams and deflections in a textbook on strength of materials.

SUPPLEMENTARY QUESTIONS

162. Is the modulus of rupture a true ultimate fiber stress? Explain.

163. What properties of the material are functions

- a. Of load carried?
- b. Of deflection?
- c. Of load and deflection considered together?

164. a. How may differences in the rate of loading be expected to affect the deflection corresponding to a given load?

- b. Should such effects be more or less pronounced as the ultimate load is approached? Explain the basis for the answer.
- c. Can a beam support its maximum load indefinitely?
- d. Will the deflection remain unchanged indefinitely under half the maximum load?

165. a. In what ways may a beam fail?

- b. Distinguish between a primary failure and a secondary failure.
- c. Is it always possible to determine the primary cause of failure from study of a fractured specimen? Explain.

166. Discuss the relative significance and usefulness of toughness at the ultimate load and toughness at rupture. Which is the larger quantity?

167. With all other factors unchanged show the effect upon both the elastic strength and the elastic stiffness of a beam if in turn each of the following elements is doubled:

- a. Width.
- b. Depth.
- c. Span.
- d. Modulus of elasticity of the material.

168. Is the strength of a beam under a static load necessarily related to its stiffness?

169. Cross out the wrong term or terms in each of the following statements. With all other factors unchanged the elastic deflection of a beam

- a. Varies inversely directly as I (I = moment of inertia of cross section).
- b. Varies inversely directly as E (E = Young's modulus).
- c. Varies inversely directly as L , L^2 , L^3 (L = span).
- d. Varies inversely directly as stiffness.
- e. Varies, does not vary with the strength.
- f. Varies inversely directly with the load.

170. For precise flexural testing, it is desirable that one support be free-swinging or on a rocker to yield readily to any tendency for the distance between supports to vary as the beam deflects. Will the lack of this adjustment tend to increase or decrease the amount of the deflection under a given loading? Why?

171. In precise flexural testing a rocker which permits lateral adjustment is often used under one support, and the load may be applied through a spherical bearing block.

- a. What may such devices be expected to accomplish?
- b. Would lateral rockers under each end, combined with a spherical bearing block under the load, add anything to the precision attainable? Explain.

172. Frequently a testing machine for beams weighs one reaction and the weighing device is calibrated to read twice the value of the reaction.

- a. With a load P at the center of the span, what is the reaction and what is the load reading?
- b. With load P at $\frac{3}{8}$ of the span L from the weighing reaction, what is the value of the reaction and of the load reading in terms of P ?
- c. If P is at $\frac{5}{8}L$ from the weighing reaction, what are these values?

173. a. Referring to Art. 57, why should several different diameters of flexural test specimen be specified for cast iron in A.S.T.M. Designation A48-41?

- b. Why should a different span be specified for each of the different diameters?

174. a. Using the notation of Art. 59, demonstrate the validity of the expression

$$aL = \frac{d S_r}{4 S_e}$$

- b. Show that a cannot have a value above 0.5 and that aL is independent of the distance between loads for values of a below 0.5.
- c. Show that this expression reduces to that of Art. 57 for a concentrated load at mid-span.
- d. Why do these expressions give only approximate values even if S_r and S_e are quite accurately known?
175. a. If a beam fails by diagonal tension instead of by shear in a region where the shear is high, what stress should be used for the limiting strength in shear in determining the resistance of the beam?
- b. A standard test beam made of a concrete having an ultimate compressive strength of 4000 p.s.i. has a modulus of rupture of about 800 p.s.i. and a tensile strength (assumed to be the same in all directions)

of about 400 p.s.i. If a bending failure is desired, what is about the least distance from the supports at which the loads can be applied? The actual shearing strength of this concrete is nearly equal to its compressive strength, the value being irrelevant since failure from shear will always be in diagonal tension (at 400 p.s.i.).

- c. For timber having a modulus of rupture of 10,000 p.s.i. and an ultimate horizontal shearing strength of 500 p.s.i. what is the limiting value of aL if failure by horizontal shear is to be avoided? Give an illustration.
- d. What is the necessary limiting relationship between aL and the diameter of a gray cast-iron bar which has a modulus of rupture of 40,000 p.s.i. and a tensile resistance, in any direction, of 20,000 p.s.i.?

PROBLEM 10

Flexural Test of Timber

A. Object.—To observe the flexural behavior of a small clear timber specimen and to evaluate some of its properties.

B. Specimen.—Wood beam 2 by 2 by 30 in. nominal dimensions.

C. Special Apparatus.—Deflectometer and bearing plates.

D. References.—Articles 28-43, 56-60. A.S.T.M. Designation D143-27 and chapters on stresses in beams in the textbook on mechanics of materials. For supplementary reference see also A.S.T.M. Designations D198-27 and D9-30 and textbook on properties of materials. The "Wood Handbook," by R. F. Luxford and George W. Trayer of the Forest Products Laboratory, gives basic information on wood as a material of construction with data for its use in design and specifications.

E. Determinations to Be Made.

1. Elastic strength. — $S = \frac{Mc}{I}$
- a. Proportional limit. — $S = \frac{Mc}{I}$
- b. Johnson's apparent elastic limit. — $\Delta = \frac{PL}{AE\delta}$
2. Modulus of rupture. — $S = \frac{Mc}{I}$
3. Modulus of elasticity. — $\Delta = \frac{PL}{AE\delta}$
4. Apparent maximum unit shearing stress.
5. Resilience of specimen.
6. Modulus of resilience of material. — $= \frac{S^2}{2E}$
7. Total work to ultimate load.

8. Average amount of energy absorbed per unit volume in stressing the beam to the ultimate.

9. Manner and type of failure.

F. Procedure.

1. *Preparation for the Test.*—Measure the length of the specimen and the height and width at mid-span. If not designated otherwise, place the specimen so that load will be applied at mid-span through the bearing block to the tangential (flat-sawn) surface nearest the pith. Adjust bearing blocks and supports to a 28-in. span and arrange the deflectometer to measure center deflections. Compute the probable ultimate load from an assumed modulus of rupture of 10,000 p.s.i., and check with the instructor. Select increments of load that will insure at least 10 readings below the ultimate.

2. *Performance of the Test.*—Apply the load slowly and continuously, taking readings of load and deflection simultaneously without stopping unless it becomes necessary to reset the deflectometer. Be on the alert to secure readings of both load and deflection at the ultimate. The test will extend to failure unless the instructor designates otherwise. Two or more readings should be obtained beyond the ultimate. Record the load and approximate deflection at failure. Sketch the manner of failure and classify in accordance

Timber

$S = \frac{Mc}{I}$
 $I = \frac{1}{12}bh^3$
 $10,000 = \frac{M(14)}{I}$
 $M = 13,333$
 $P = 9500$

$$S_R = \frac{Mc}{I}$$

with the types of failure shown in A.S.T.M. Designation D143-27, Art. 48. Test one of the ends on an 8-in. span. Record only the ultimate load. Sketch and identify the failure.

G. Report.

- ① 1. *Graph Sheet*.—Construct a load-deflection diagram with loads as ordinates.
- ① 2. *Results*.—Tabulate all the indicated properties for the first test and the apparent maximum flexural and shearing stresses for the second test.
- ② Indicate the type and probable cause of failure in each test.

H. Supplementary Questions.

176. How should the modulus of rupture and the modulus of elasticity of a small clear specimen such as this one compare with the corresponding properties as determined from testing a full-size structural member?

177. a. How should the values of the modulus of rupture and modulus of elasticity of a saturated specimen compare with the corresponding values for a dry specimen?

b. What constitutes essential saturation for timber?

178. How does the relative importance of shearing and bending stress vary with the span? Why?

179. Suppose that the movement of the applied load after contact was established had been taken as deflection and that the load and supports cut into the specimen appreciably.

a. For which of the properties would the values obtained have been affected thereby? Indicate which values would

have been increased and which decreased and why.

b. Was the method used for measuring the deflections proof against inaccuracies of this kind? Explain.

180. Both tension and compression are present in bending.

a. Is timber rated stronger in tension or in compression?

b. Was there evidence from the test in support of this?

181. The deflection used in the evaluation of properties included that due to shear.

a. Are the results seriously in error? Explain. (Show approximate computations.)

b. Is the value obtained for Young's modulus larger or smaller than it would have been had separate account been taken of the portion of the deflection which is due to shear?

182. How would you expect the value of Young's modulus in flexure to compare with those in tension and compression

a. If the moduli in tension and compression are equal as is assumed in the derivation of the flexure formula?

b. If they differ?

183. In comparison with other structural materials is timber relatively resilient, tough, strong for its weight, brittle, stiff, elastic, ductile?

184. Why in Item E4 was the maximum unit shearing stress qualified by the word "apparent"?

PROBLEM 11

Elastic Curve of a Beam

A. **Object**.—To determine experimentally the elastic curve of a beam under a concentrated load.

B. **Specimen**.—Steel or timber beam.

C. **Special Apparatus**.—Reference bar and dial indicators for measuring deflection at points along the beam.

D. **Reference**.—Chapter on deflections in textbook on mechanics of materials.

E. **Determinations to Be Made**.

1. Modulus of elasticity of material.

2. Elastic curves of beam at different loads.

F. **Procedure**.

1. *Preparation for the Test*.—The instructor will designate the span, point of application of the load, and points along the beam at which deflections are

to be observed. Determine the cross-sectional properties of the beam from measurements taken at mid-span. Compute the total load to produce the specified working stress for the material,¹ and deduct the weight of the setup to determine the maximum additional load to be applied. Attach the reference bar in such a way that it will not deflect with the beam, and mount the dials on the bar.

2. *Performance of the Test*.—Record the dial readings for the initial or zero load. Apply the allowable load in three equal increments, taking dial readings for each. Before the second and third increments of load are applied, check each dial to

¹ Steel = 20,000 p.s.i.; timber = 1000 p.s.i.

$$S = \frac{Mc}{I}$$

$$20,000 = \frac{I \cdot Mc}{I}$$

$$M = \frac{Wc}{4}$$

see if there is sufficient range available to measure the increment of deflection, and if not, reset the dial and record the new reading. Remove the load in the same increments, checking dial readings.

G. Report.

1. *Graph Sheet.*—Within the lower one-fourth of the graph sheet plot a load-deflection diagram for the point at which the measured deflection was the greatest for the maximum load. Near the top of the sheet draw a dimensioned line diagram of the beam showing the location of the load and the points at which the deflections were measured. From this as a horizontal axis, plot the curves for the measured and calculated deflections (see under Results) for each increment of loading. Directly below the elastic curves construct the shear and moment diagrams for the maximum load on the beam.

2. *Results.*—Determine the modulus of elasticity of the material from the load-deflection diagram for the dial location at which the measured deflection was the greatest.² Using this value of E , calculate the deflections corresponding to each of the measured deflections. Compare the measured and calculated deflections.

H. Supplementary Questions.

185. *a.* What relationship do the calculated deflections at one-third load bear to those at full load? Why?

b. From the standpoint of practical accuracy, why is the full load preferable to the one-third load as the basis of calculation?

186. At which point along this beam should the observed and computed deflections always agree? Why?

187. If the calculated deflections had been based on an assumed value for Young's modulus, the differences between the observed deflections and computed deflections would then be due to either or both of two causes. Explain, indicating the characteristic difference for each cause.

188. Explain why the method used for the determination of Young's modulus is preferable to a computation based on a single observation of load and deflection.

189. The beam had some initial deflection due to its own weight and the small steadying load.

² Note that this is not necessarily the point of maximum deflection for the beam. The location of that point does not necessarily correspond to that of any dial.

a. Do these appear in the plotted curves? Explain.

b. Lack of initial straightness would change the shape of the beam. Should it alter the shape of the plotted elastic curve? Explain.

190. *a.* Between what points along the beam should the section of maximum deflection be located?

b. Under what conditions should it be located under the load?

191. If one dial had reached its limit of motion without being reset, how would the plotted point appear relative to the others?

192. *a.* Would the actual, or observed, deflection be greater or less than that computed if the outer fibers of the beam were stressed beyond the elastic limit?

b. Could the deflection be computed readily for such a case? Explain.

193. If the beam tested had had a cross section that was unsymmetrical with respect to a vertical longitudinal plane, should agreement between the observed deflections and those computed by the usual equations be expected? Explain.

194. The reference bar was supported by the beam at points directly over the supports. Would it have been proper to have supported the dials on the bed of the testing machine? Why?

195. For timber beams, it is well to distribute the load slightly at the point of application and at the supports to prevent local crushing. Would settlement such as that from local crushing introduce error in the readings of deflection

a. As they were measured?

b. If the reference bar had rested on the supports rather than on the beam itself?

196. Some deflection is caused by shear.

a. Relative to the deflection caused by moment, is the deflection due to shear more important for a beam on a short span or on a long one? Why?

b. Did the deflection as measured include that due to shear?

c. In precise work, should account be taken of the shear deflection?

d. What is the approximate value of the maximum shear deflection for the largest load of the test if the modulus of rigidity is assumed to be two-fifths of the modulus of elasticity?



197. *a.* Is it equally simple to calculate deflections between the left support and the load and between the load and the right support? Explain.
- b.* The load is at $L/4$ from the left support, and the maximum deflection is to be calculated. Can you offer a simplifying suggestion?
198. At a point of concentrated loading on a beam what change takes place
- a.* In the shear diagram?
- b.* In the moment diagram?
- c.* In the elastic curve of the beam itself?
- d.* What is the significance of a discontinuity in the elastic curve of a beam?
199. *a.* What does a discontinuity in a shear or a moment curve indicate?
- b.* What is a point of zero moment called? What, if any, significance does it have relative to the curvature of the beam? Why?
- c.* Does the moment curve indicate whether the elastic curve is convex or concave upward?
200. *a.* The shear is constant in a region of zero load. Why?
- b.* The bending moment is constant in a region of zero shear. Why?
- c.* The slope is constant in a region of zero moment. Why?
- d.* The deflection is constant in a region of zero slope. Why?
201. *a.* What is meant by the degree of an equation?
- b.* Illustrate by citing equations of different degrees from flexure theory.
- c.* What is the form of the elastic curve of a beam in a region of constant moment?

PROBLEM 12

The Strain Gage

A. Object.—To determine stresses in an assigned structural member by means of a strain gage and to compare the results with those from analytical determinations.

B. Specimen.—A steel I-beam, or other assigned structural unit.³

C. Special Apparatus.—A strain gage and a reference bar.

D. References.—Article 12. Table of cross-sectional properties of I-beams.

E. Determinations to Be Made.

1. The strain-gage constants.
2. Strains on assigned gage lines in a region of constant moment.
3. Location of the neutral surface as indicated by the above measurements.
4. Stress increments corresponding to the measured increments of strain.
5. Corresponding stresses as computed from the generally accepted theory of flexure.

F. Procedure.

1. *Preparation for the Test.*—Obtain the cross-sectional properties of the beam from a handbook after identifying the beam from measurements of its depth, flange width, and web thickness. Deter-

mine the load which will produce a maximum computed stress increment of 16,000 p.s.i. in the beam and check with the instructor. Number the gage lines, and determine the mean distance of each from the lower face of the beam. Practice using the strain gage until readings on a given gage line can be duplicated.

2. *Performance of the Test.*—Record the temperature in the laboratory and take a reading on the reference bar. Take strain-gage readings on the gage lines in order, and repeat in order until two readings which agree within one dial division have been obtained for each gage line. Apply the computed load, and again take strain readings, using the same procedure as above. Reduce the load to its initial value, and take another set of zero readings, followed by a closure on the reference bar. If at any stage, data appear to indicate a shift in instrumental adjustment, take a check reading on the reference bar.

G. Report.

1. *Graph Sheet.*—Plot the measured unit strains as abscissas against the vertical location of the respective gage lines as ordinates. Include a supplementary scale along the x axis to indicate the corresponding values of unit stress using an appropriate value of E for the material. Plot to the same axes the line which indicates the stress distribution as computed according to flexure theory.

³ Outline is based on assumption that the member to be tested is a steel I-beam under symmetrical two-point flexural loading. Specific items will vary with type of specimen, nature of loading, and kind of material used.

For both stresses and strains plot tension to the left and compression to the right. Indicate the experimentally determined location of the neutral surface.

2. *Results.*—Determine the strain-gage constants as (a) the unit strain corresponding to one division on the dial of the strain gage and (b) the unit stress corresponding to one division on the dial of the strain gage, assuming $E = 30,000,000$ p.s.i. Show the locations of loads and reactions on a dimensioned line diagram, and beneath it construct the shear and moment diagrams for the full-load condition.

H. Supplementary Questions.

202. Are the results in accord with the theory of stress distribution in beams?

203. Compare this test with the precise tension test in the following respects:

- Quantities measured.
- Properties to be determined.
- Assumptions made.

204. Initially (as the zero-load readings were taken) the beam was already under some stress, since it supported its own weight and a small additional load to steady the setup.

- Were these stresses included in the strain-gage determination? Explain.
- Would initial stresses from cooling or from cold-working be shown by a strain gage?
- In general, what effect do initial strains, whether from load or from other causes, have upon the strain-gage readings?

205. For the strain gage and specimen that were used, compute the stresses, if possible, corresponding to dial differences of 10, 30, and 200 divisions. If not possible, explain why.

206. Compute the constant for strain and for stress for a 12-in. strain gage for which one dial division equals 0.0002 in. total movement of movable leg. The gage is to be used for stress determinations on concrete having a modulus of elasticity of 3,000,000 p.s.i.

207. What are the advantages of the two-point symmetrical loading that was used

- From the standpoint of shearing effects?
- From the standpoint of stress conditions along a gage line?

208. Give reasons why neither the experimental nor theoretical stress is necessarily the true stress in the beam.

209. A set of strain-gage readings was taken on a concrete arch after which some load was applied

and another set of readings was recorded. The load remained on the arch for several hours, after which a third set of readings showed that considerable additional deformation had occurred. Is this an indication that the arch was under increased stress? Explain.

210. A 10-in. strain gage is of ordinary carbon steel. While in use the warmth of the hands raises the temperature of the metal 10 F.

- What is the error from this source in the total strain within the gage length?
- If the measurements are on steel, what is the error in pounds per square inch? (The temperature of the steel of the structure or member under test has not changed.)
- What is the error in pounds per square inch if the measurements are on concrete which has a value for E of 4,000,000 p.s.i.?
- Should the errors in observed stress vary for different gage lengths?
- What precautions should one introduce in the testing technique in order to detect errors from chance or unsuspected sources?

211. A strain gage may be made of ordinary steel or of invar steel. The Whittemore form of the fulcrum-plate strain gage is made of invar steel, and in addition the dial indicator is so attached that the slight change of length that can occur in the frame of the gage tends to be offset by the change in length that occurs in the stem of the dial. Thus for any ordinary range of temperature change the changes in the gage may be considered to be negligible. Compare the use of such a gage with one of ordinary steel on a steel member under each of the following situations:

- Observations under conditions of approximately constant temperature for both gage and member.
- Observations in which the gage is subjected to changes of temperature but the member is not.
- Observations in which the member but not the gage is subjected to changes in temperature.
- Observations under conditions of variable temperature which apply to both gage and member
- Discuss the use of reference bars of invar and of ordinary steel.

212. Gage holes should be of the designated diameter and deep enough to prevent the point of the gage leg from touching bottom. How should a difference in the diameter of gage holes or touching the bottom of the hole alter the readings obtained

- a. With a gage of the Berry type in which the movable leg is part of the lever system?
- b. With a gage of the fulcrum-plate or Whittemore type?

213. Outline procedures whereby a strain gage might be used to determine

- a. The effect upon the stress in one or more members of a bridge from the passing of a truck.
- b. Plastic flow in a timber column that supports a part of a building.
- c. Added stresses in the steel and concrete of a stadium under the influence of a cheering crowd.
- d. A specified limiting prestress to be placed in a hoop that is being bolted around a silo.

e. The amount of opening and closing of an expansion joint in a pavement, due to temperature and moisture changes in the concrete.

f. Observations on a member of a radio tower at intervals during a period of several months.

214. The line representing the calculated unit stresses may differ from the line representing the unit stresses obtained from the strain gage by one or both of the following:

- a. A difference in slope. How might this be explained?
- b. A horizontal displacement. How might this be explained?
- c. Determine the value of the modulus of elasticity that would produce the best agreement between the calculated unit stress and the unit stresses as obtained from the strain-gage readings. Indicate whether or not such a value is within reason for the material tested.

CHAPTER VIII

COLUMN TESTS

62. Use.—For the most part column tests are made to determine the properties of the column as a structural unit rather than the properties of the material of which the column is composed; although the modulus of elasticity may be determined from a properly conducted test of a slender column.

63. Test Specimens.—There are no standard dimensions for test columns, each column or series being planned for specific research purposes or to illustrate certain characteristics of column action. There is no definite boundary between a long compression member and a short column, as one shades gradually into the other. In Chap. V, a height-diameter ratio of $10(h/d = 10)$ was set more or less arbitrarily as the upper limit of slenderness for a compressive specimen (see footnote, page 48). For a circular specimen this amounts to a slenderness ratio of 40. Many of the concrete and timber columns of building construction are virtually in the transition zone between columns and simple compression members.

64. End Conditions.—The degree of restraint at the ends of a column has an appreciable effect on its behavior under load. The difficulty of accurately determining the degree of end restraint complicates the interpretation of column-test results. The greatest uncertainty is likely to be with the short and intermediate lengths of column. A long, or Euler, column with the ends fixed will support four times the load that it would if the ends were free to turn about frictionless pins.

In tests designed to demonstrate or verify column theory, the round- or pivot-end condition is nor-

mally selected as being the simplest condition to simulate.

SUPPLEMENTARY QUESTIONS

215. Determine the slenderness ratio

- a. Of a square column having a height-breadth ratio of $10(h/b = 10)$,
- b. Of a circular column having a height-diameter ratio of $10(h/d = 10)$.

216. In selecting the round- or pivot-end condition for experiment, the end condition corresponding to the least ultimate load has been chosen. Is this objectionable?

217. a. The resistance offered by a slender (Euler) column is a function of what property of the material?

- b. Is the same property important in its influence on the load that a short column will carry?

218. a. For a beam, Young's modulus may be determined from load-deflection data. In general, is this true for a column? Why?

- b. How may Young's modulus be evaluated from column data? Indicate any special conditions that must be met.

219. The interior columns of a building are likely to be more critically stressed if only the alternate bays are loaded than if all bays are loaded, even though the columns are carrying only half the total load that they would if all bays were loaded. Why should this be true?

PROBLEM 13

Tests of Small Timber Columns

A. Object.—To determine experimentally the relationship between the slenderness ratio and the ultimate average unit load supported by small timber columns pinned at the ends.

B. Specimen.—Small, straight-grained piece of timber of uniform cross section.

C. Special Apparatus.—Two fixtures for producing the pin-end condition by minimizing end restraint.

D. References.—Articles 62–64. Chapter on columns in textbook on mechanics of materials.

E. Determinations to Be Made.

1. Modulus of elasticity of the material.
2. Ultimate compressive strength of the material.
3. Equations of the following curves as applied to timber of the quality tested:

- a. Euler's.
- b. Straight-line.
- c. Rankine's.

F. Procedure.

1. *Preparation for the Test.*—Measure the cross section of the specimen at mid-length and attach the end fixtures with the knife-edges or pins parallel to the longer dimension. Measure the effective length of the column as the distance between knife-edges or centers of pins, and compute the probable maximum load by Euler's formula.

Place the assembly in the testing machine with the axis of the pins normal to the front of the machine (orientation such as to minimize personal hazard should the specimen break abruptly or fly out of the testing machine).

2. *Centering and Adjusting the Column.*—Comparative tests need to be made under conditions which can be duplicated with reasonable ease and precision. Since it is very difficult, if not impossible, to produce a fixed-end condition and since the effects of partial end restraint cannot readily be evaluated, these tests will be conducted using the pivot- or pin-end condition to minimize end restraint.

Freedom from eccentricity is likewise essential. Very small errors in the placement of the column in the column ends and a slight lack of straightness or nonuniformity in the column itself will introduce significant eccentricity either of load or of resistance.

The column may be approximately centered between the pins or knife-edges by eye after which the final adjustment is best made by trial loading, as follows: Apply load slowly until a slight bend in the column is noticed. Flex the column through the central position a few times, and note whether or not it is easier to move in one direction than the other. If there is a difference, the column is eccentric. Release the load, adjust the column in the column ends to reduce the eccentricity, and reload. Repeat until the column may be bent with equal ease in each direction.¹

¹ In a machine in which the load is measured on a dial, the central position may be determined more directly by adjusting until the load readings at the two extreme positions agree.

For a slender column the maximum load is reached just as deflection becomes apparent. That load represents the maximum that the column can carry for that condition of placement; for, if that load were free to follow down, the column would continue to deflect until it collapsed. The column will carry the greatest load when the eccentricity is zero. The highest resistance developed during the trial loadings is recorded, therefore, as the ultimate for the column. Because the head of the testing machine is not free to follow down, the ultimate load can be applied, recorded, and removed without producing permanent set or visible damage. For a slender (Euler) column the action will have been entirely elastic.

3. *Conduct of the Test.*—Center the column by trial as outlined above, and determine the maximum load it will support. Then remove it from the machine, and cut from one end two specimens of equal length such that they will be suitable for simple compressive tests. Test the remaining length as a column, then cut it into two unequal lengths, so chosen as to provide well-spaced points on the graph, and test each section. Test one of the two short lengths originally cut from the long column as a short pin-end column. Test the other short piece as a compressive specimen in order to determine the compressive strength of the timber.

G. Report.

1. *Graph Sheet.*—Using slenderness ratios as abscissas and the average ultimate unit loads (P/A) as ordinates, construct the curves

- a. For the experimental data.
- b. For Euler's formula.
- c. For the straight-line formula.
- d. For Rankine's formula.

Dot in any portions of the curves that you consider not to be in reasonable agreement with the data secured.

2. *Results.*—Evaluate Young's modulus² and the ultimate compressive strength of the material.

Write the Euler formula, and derive a straight-line formula and a Rankine formula for this material. Obtain the straight-line formula from the graph by drawing the line from the ultimate strength at $L/r = 0$ tangent to Euler's curve. Use Ritter's rational constant in developing the Rankine formula. Indicate the range of slenderness ratios over which each formula appears to be applicable.

² Obtained by substituting in Euler's formula for round-end columns the maximum load carried by the longest column.

H. Supplementary Questions.

- 220.** *a.* In a testing machine it is possible to test a slender column to the ultimate without structural damage. Explain.
- b.* In any case in which a structural column has reached its ultimate load without the collapse of the structure, what must have occurred?
- c.* Would this be possible in a structure in which the load was free to follow the column? Explain.
- 221.** In general, column action is a combination of direct stress and bending as expressed by the equation $S = \frac{P}{A} + \frac{Mc}{I}$.
- a.* For what limiting condition may the first term be omitted without serious error?
- b.* The second?
- 222.** *a.* What ultimate load should a 4-in. square column of this timber 10 ft. long be able to carry on the basis of the test?
- b.* Practically, should the full-size member have a higher or a lower value of P/A for a given slenderness ratio and end condition? Why?
- c.* How should a knot near one face affect the load-carrying capacity? Explain.
- 223.** At about what value of slenderness ratio does increased length begin to have an important effect on the ultimate load that can be supported? What would this value be in terms of length over diameter (or least lateral dimension)
- a.* For a rectangular column?
- b.* For a circular column?
- What are the slenderness ratios for specimens which have heights twice their least lateral dimensions if the cross sections are
- c.* Rectangular?
- d.* Circular?
- 224.** From the evidence of Question 223 should the different proportions of the specimens listed in Chap. V on compressive testing have an important bearing on the relative loads which they carry?
- 225.** Does the fact that the longer members support less total (and unit) load mean that the material in a long member is less strong or that it is less stiff than that in a short member? Explain.
- 226.** *a.* What property of the material determines the load that a short compressive member may support?
- b.* A slender compressive member? Why?
- 227.** *a.* Why is it possible to push a deflected Euler column easily from one extreme deflected position to the other while it is carrying its maximum load?
- b.* Would a plot of loads against deflections be significant for a slender (Euler) column for loads between zero and the ultimate? Why?
- 228.** Would it be proper to design columns on the basis of the formulas derived in this test? Explain.
- 229.** *a.* If there were appreciable frictional restraint in the end fixtures, would the ultimate loads be increased or decreased?
- b.* How would the value obtained for modulus of elasticity be affected?
- 230.** *a.* Why were special end fixtures used?
- b.* Would the columns have been less strong without them? Explain.
- c.* Does the use of the fixtures more nearly duplicate practical conditions?
- 231.** From the standpoint of material the small column was probably relatively stronger than a full-size column in a structure. From the standpoint of usual loading conditions the small column was probably less strong. Why?

CHAPTER IX

HARDNESS TESTS

65. Discussion of Hardness.—The term *hardness* as applied to materials is used to convey a number of meanings. Hardness may denote resistance to abrasion, to scratching, or to cutting, or it may denote brittleness, stiffness, resilience, toughness, high strength, or combinations of these properties. Two of the most widely used tests of hardness, the Brinell and Rockwell, are indentation tests; while a third, the scleroscope test, gives virtually a measure of the resilience of a material.¹ Other types of tests involve cutting, scratching, or abrasion.²

The hardness tests mentioned above are applicable primarily to metals, although some of them are used occasionally with other materials. The geologist employs various scratch tests in the identification of minerals, and different forms of abrasion tests are employed for paving brick and stone. Variations of the Brinell hardness test have been used on concrete and in the testing of timber, although the distinction between hardwoods and softwoods, so called, is not based upon physical hardness, or any test therefor.

The discussion of hardness in this chapter is restricted to metals. For several of these there is a reasonable correlation between ultimate strength and the hardness indexes and also between the endurance limit and the hardness indexes obtained from Brinell, Rockwell, and scleroscope tests. In turn these indexes can be correlated one with another. For some other types of material, such as rubber or glass, there may be little or no correlation between indexes based upon such fundamentally different properties as are involved in indentation and in resilience tests.

Hardness tests may be made to measure one of the several manifestations of hardness, but more

¹ For this reason, the scleroscope number of rubber may be expected to be high as compared with steel. For example, a soft rubber with a proportional limit of about 150 p.s.i. and a modulus of elasticity of 350 p.s.i. will have a modulus of resilience of 32 in.-lb. per cu. in., which is about twice that of structural steel.

² A form of hardness test especially suited to very hard materials is the mutual indentation test (see reference, Art. 67e).

frequently they are used as a check on, or as an indirect measure of, other properties. They often constitute a convenient nondestructive test to determine whether or not the material is in the physical state which other tests, generally destructive, have shown to be suitable. If a metal is of uniform composition and has been produced by a well-controlled process of manufacture, uniform indentation-hardness numbers are nearly always a sufficient guarantee of its uniform quality. Uniformity in quality may include such factors as uniformity of grade of metal, exactness of temper in heat treatment, and homogeneity of material. The tensile³ strength of steel can be estimated with sufficient accuracy for many commercial purposes from its Brinell hardness number. The indentation test may be preferred to a tensile test for control purposes because it is nondestructive and relatively inexpensive to make and can be applied to units of the regular factory output. Since the test rarely impairs the usefulness of the product, it is often feasible to test the entire output. Even where tensile tests to destruction are desirable, indentation tests may be made on the entire output to select the specimens which should show the widest range of variation in strength.

66. Current Methods of Test.—The Brinell test is most commonly used in laboratory work. In industry the Rockwell test is more common because it gives quick and accurate results and little experience is required of the operator. The scleroscope test is relatively less important than formerly. However, it is about the only test which can be used for testing very small metal articles such as watch springs and hardened faces of gear teeth.

a. Brinell Method.—The Brinell method consists in applying a load⁴ to the specimen through a

³ True also for compressive strength which for steel differs little from the tensile strength. The formulas applicable to the tensile strength of steel also give good approximate values for the compressive strength of cast iron which may be from four to six times its tensile strength.

⁴ A load of 3000 kg. is specified for ferrous metals and alloys. For other materials a load of 500 kg. is specified

hardened steel ball 10 mm. in diameter for a specified minimum time.⁵

The Brinell hardness number is the standard load divided by the spherical area of the imprint and is expressed in kilograms per square millimeter. Since the area of the impression can be expressed in terms of either the diameter or the depth of the impression, the hardness index may readily be obtained from a table or curve if either the diameter or depth of the impression has been measured. Brinell hardness apparatus usually includes the ball and provision for the hydraulic application of load. Such an assembly is convenient but not essential since a ball in a suitable block may be used with a small testing machine hand-operated. Usually the diameter of the impression is measured, since the material pushed up near the margin of the crater may make the measurement of depth less precise.

Primarily to facilitate measurement, the surface upon which the impression is to be made should be polished, this requirement being more important for the harder grades of metal. The thickness of the specimen should be at least ten times the depth of the impression. The impression should be placed far enough from the edge of the specimen to avoid lateral bulging. The Brinell ball will need to be checked frequently for distortion when being used for testing material with a Brinell number above about 400 (steel with an ultimate strength of 200,000 p.s.i. has about this hardness).

Among the most used of the many formulas for estimating the tensile strengths (S) of steels and steel alloys from Brinell numbers (B) are the following:

Abbott:

$$S = 700B - 26,000$$

Dohmer:⁶

$$S = 515B \text{ for } B < 175$$

$$S = 490B \text{ for } B > 175$$

Note that the tensile strengths of steels and the compressive strengths of cast irons are approximately 500 times their Brinell hardness numbers.

since the greater load would make a larger indentation than necessary.

⁵ Ten seconds is specified for ferrous and 30 sec. for most other metals. For most materials application for a few additional seconds does not increase the size of the impression appreciably.

⁶ Petrenko, S. N. Relationships between Rockwell and

b. Rockwell Method.—The Rockwell method also measures the resistance of the material to plastic indentation. A load of 10 kg. is applied through a steel ball $\frac{1}{16}$ in. in diameter. An increment of 90 kg. is then applied and the increment of penetration measured. This increment is indicated on a scale as the Rockwell hardness number. For harder specimens a diamond tup is used instead of a steel ball, and the total applied load is 150 kg. The Rockwell method produces a much smaller impression than the Brinell method and consequently produces less disfigurement, but it may be more affected by local conditions in the material. There are various modifications of the Rockwell test which are intended to increase its adaptations, especially to tests of thin sheet metal.

c. Shore Scleroscope.—In this method a small steel or diamond tipped weight is dropped on the specimen from a fixed height, and the height of rebound is measured. This is primarily an indication of the resilience of the material, but for ferrous metals it gives values comparable to the Brinell method, the Brinell number being approximately six times the scleroscope number. The scleroscope test has the advantage of leaving only a very small permanent indentation on any but relatively soft and ductile specimens.

For this test it is important that the surface be flat, smooth and clean. A film of oil may lower the height of the rebound materially. It is also essential that the diamond point be tested frequently on the test block supplied with the machine in order to detect any change due to chipping of the diamond.

d. Vickers' Method.—With the Vickers Hardness Tester the impression made by the corner of a diamond cube is measured after the application of a definite load. This test is used to some extent in research work.

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 - (4) Tinius Olsen Testing Machine Company, Philadelphia, Pa.

SUPPLEMENTARY QUESTIONS

- 232. Describe briefly the Brinell, the Rockwell, and the scleroscope hardness tests.
- 233. Can a satisfactory comparison of two dissimilar materials be obtained from their hardness numbers?
- 234. Can an approximate value of the ultimate strength of brass or rubber be obtained from the Brinell hardness number and Abbott's formula?

235. Is the relationship between Brinell hardness number and ultimate strength rational or empirical?

236. Why does dirt or a film of oil decrease the apparent hardness as determined with the scleroscope?

237. a. In what units is the Brinell number expressed?

b. Are the Rockwell and scleroscope numbers in any definite units?

c. Is the property of hardness expressed in definite units analogous to those for strength, stiffness, toughness, or resilience?

238. Does it seem reasonable that the relative hardness of a given metal should be a good index of its fatigue strength (endurance limit)?

239. Designate a situation in which the scleroscope test is superior to the Brinell and the Rockwell tests.

240. Is a hardness test necessarily, or even usually, employed because it is the property of hardness that is desired? Explain.

241. Why do instructions specify the period during which the pressure is to remain on the Brinell ball?

PROBLEM 14

Hardness Tests

A. Object.—To study hardness and to determine hardness indexes for assigned specimens of metal.

B. Specimens.—Pieces of ferrous and nonferrous metals of proportions suitable for test.

C. Special Apparatus.—One or more of the following: Brinell equipment with measuring microscope, Rockwell hardness tester, Shore scleroscope.

D. References.—Articles 65-66. A.S.T.M. Designations E10-27 and E18-36.

E. Determinations to Be Made.

1. Brinell hardness numbers.
2. Rockwell hardness numbers.
3. Scleroscope hardness numbers.
4. Estimated strengths of all ferrous specimens from Abbott and Dohmer formulas.
5. Ratio of Brinell numbers to scleroscope numbers.

F. Procedure.

1. *Brinell Method.*⁷—Follow the procedure outlined in A.S.T.M. Designation E10-27.

⁷ In case the load is applied in an ordinary testing machine or the diameter of impression is measured in inch units, the

2. *Rockwell Method.*—Follow the procedure outlined in A.S.T.M. Designation E18-36.

3. *Scleroscope Method.*—Place the reference block on the anvil, and lower the tube until it is in contact. Release the weight, and observe the height of rebound. Lift the weight back into position at the top of the tube before it bounces again. Move the specimen, and repeat, taking the average of the two observations for the scleroscope number of the reference block. Then place the specimen on the anvil, and record two observations upon it. Do not let the weight fall twice on the same spot.

G. Report.—Tabulate the results, and compare with standard values.

H. Supplementary Questions.

242. Is the Brinell indentation truly spherical? Explain.

following conversion factors may be used: 3000 kg. = 6614 lb., 500 kg. = 1102 lb., 0.001 in. = 0.0254 mm.

243. In a Brinell test why is a polished surface to receive the impression more important for the harder materials?

244. Will side bulging because a Brinell impression is taken too near the edge result in a hardness number greater or less than the value obtained by the correct procedure?

245. Why is a minimum thickness of at least ten times the depth of the impression required in the

Brinell test? How should the value obtained be influenced by specimens which are too thin, assuming that they are tested on a heavy anvil which is

a. Harder than the specimen?

b. Softer than the specimen?

246. Outline a hardness-test procedure whereby evidence could be secured easily and indestructively regarding the quality of ferrous metal in a bridge member, a machine, or a building.

CHAPTER X

FATIGUE AND IMPACT TESTS

68. Repeated and Impact Loading.—Experience shows that the resistance of a material to failure under a load is dependent upon the manner of application of the load. A member which is adequate to support a load without failure often fails under a load of equal magnitude applied repeatedly or abruptly. It is necessary, therefore, to classify loads on the basis of their method of application. Three general types of loading are recognized: static loading (short-time and sustained), repeated or fatigue loading, and impact loading.

Static loads are loads which remain in place (*e.g.*, dead loads) or other loads which are applied or removed slowly. Repeated or fatigue loading relates normally to loads which are applied and removed a large number of times. Most materials will fail eventually under the repeated application of loads which would be safe if applied only a few times or which could, as static loads, be supported indefinitely. The failure is progressive, the rate of progress depending upon the relative magnitude of the stress developed in the immediate vicinity of the impending fracture. The mechanism of failure, that of gradual extension of the inevitable small cracks within the material, is discussed in Art. 71.

Impact loads are loads which are applied suddenly or with shock. The essential difference between static and impact loads is that an impact load always produces a peak stress higher than that produced by a load of the same magnitude if it is applied slowly. For example, if a weight is applied slowly to the end of a horizontal cantilever beam, the beam deflects slowly to a maximum. During the interval of application of the load, the stresses and strains gradually attain their maximum static values without overrun. If the same load is applied suddenly, without being dropped, the beam deflects twice¹ as much as it does under the slowly applied load, then springs back almost to the unloaded position, again deflects, and continues to vibrate

¹ Provided the proportional limit is not exceeded. If it is exceeded, the deflection will be more than twice as much and the final deflection will also be increased.

until it comes to equilibrium in the same position as it does under the slowly applied load. The stresses and strains follow the same cycle of vibrations, attaining temporarily twice the value which they would have if the same load were applied slowly. Thus the rapidly applied load not only produces a range of stress higher than that attained at any stage under a static load of numerically equal magnitude, but it also introduces elements of repeated or fatigue loading because of the induced vibrations. In design for suddenly applied loading (no shock beyond that of "instantaneous" application), the possible added adverse effect of the induced vibration is disregarded and the load is considered to stress the member twice as severely as it would if the same load were applied statically. If the load is dropped on the member, the general effect will be the same as that of the suddenly applied load, but the deflections, stresses, and strains will be more than twice as much as they would be if the load were applied slowly. Any load which causes vibration is in effect an impact load.

69. Use of Fatigue Tests.—The usual function of fatigue testing of a material is to evaluate the endurance limit, which is defined as "the highest unit stress to which a material can be subjected a large number of times (many millions of repetitions) without failure." It is evident that the endurance limit differs from the elastic strength and the ultimate strength in that it cannot be evaluated from a single test but rather requires the testing of many similar specimens at different intensities of stress either to failure or to millions of repetitions of the stress without failure.² Weeks or months of testing may be required to secure these data.

Modern technological developments have greatly magnified the importance of resistance to repeated stress, and during the past 25 years a great amount

² After the data have been secured the numerical value of the endurance limit may be determined conveniently from an *S-N* diagram—a diagram in which the stress is plotted against the number of cycles causing failure or the maximum number of cycles applied (see textbook on properties of materials).

of research on the fatigue of metals has been performed and published. The techniques of fatigue testing for research purposes are well established, but a test procedure extending over a period that may be weeks or months is too long to constitute a satisfactory test for the acceptance or rejection of a material. Much fatigue research of recent years has been devoted, therefore, to an effort to evolve a simplified short-time test procedure which can be relied upon to give a reasonably correct indication of the fatigue resistance. Various special correlations have been found between the endurance limit and such properties as hardness, proportional limit, and ultimate strength, but there is as yet no short-time test that seems to meet the need sufficiently well to warrant its adoption as a commercial standard.

70. Types of Fatigue Tests.—Material may be required to resist either static or impact repeated stresses of several types under a great variety of possible combinations. The stress (either tensile or compressive) may be axial, ranging from zero or some stress above zero to a maximum with each cycle of loading. It may be axial but involve a reversal, passing through zero from a maximum compression to a maximum tension. The repeated stress may be torsional, either direct or reversed. One of the most common manifestations of fatigue stress, which is also the basis for the most-used test for the endurance limit, is the reversed bending which occurs when a loaded beam is revolved. The extreme fibers pass from tension to compression with each revolution of the beam.

71. The Nature of Fatigue Failure.—As is pointed out by the current textbooks on materials, the breakdown of a metal member under repeated loading is a fracture which develops gradually along the crystal faces starting within an area of stress concentration near the base of a crack, a surface roughness, an abrupt change of cross section, an internal imperfection, or perhaps a scratch or tool mark.

With the advent of high-speed machinery and its many millions of successive applications or reversals of stress, it is obvious that any source of stress concentration is potentially dangerous. Consequently, current machining practice requires that all parts which will be subject to repeated stress be filleted and free from sharp corners and abrupt changes of cross section, that surfaces not only be free of scratches and tool marks, but that they be highly polished.

In general, the most severe condition is that produced by repeated impact because of the tendency of impact to produce high concentration of stress, which is exactly what is needed to start a fatigue failure. If corrosion of the metal can occur, fatigue failure may develop rapidly at a relatively low stress, the condition being known as *corrosion fatigue*. As a result of the formation and subsequent cracking (even at a low stress) of the thin, relatively brittle layer of oxide or other coating, enough of a surface discontinuity is formed to start a *bona fide* fatigue crack which can ultimately produce failure across the section. The embrittlement of boiler plate from certain caustic impurities in the water is an illustration. Stressed metals corrode more readily than do unstressed metals, a fact that aggravates the problem of corrosion fatigue.

72. Use of Impact Tests.—Impact tests are sometimes made on materials, particularly metals, because it is recognized that the resistance of a material to shock is dependent upon factors other than those which control its resistance to a steady or slowly applied load. Resistance to a slowly applied load may be measured in terms of stress, but resistance to impact involves, in addition to the capacity for developing stress, the capacity of the material for being deformed without damage. As was indicated in Chap. II, the resistance of a material to impact loading, if all the material develops the same stress, is measured approximately by the area under the stress-strain diagram.³ If the same stress is not developed throughout the entire specimen, the distribution of energy is likewise nonuniform, with the result that any determination of the shock-resisting capacity of a given material, or even of a given specimen, becomes largely empirical.

Standardized impact tests on standardized specimens have been developed to provide a basis for comparing the resistance of materials to shock. The results of such tests are valuable in a qualitative but not a quantitative sense. In general, numerical values obtained from the present standard impact tests are not valid for predicting the impact resistance of a dissimilar specimen of the same material.

73. Types of Impact Tests.—One form of impact test consists in simply dropping a weight on a

³ This is based on the usual assumption that a material resists an energy load in the same manner as it does a static load. For very rapid applications of load the validity of this assumption is doubtful.

specimen from successively increasing heights until the specimen fails. The impact or energy load causing failure is taken as the weight multiplied by the height of final drop. Such a procedure disregards the probable weakening effect of the blows received prior to final failure.

The Turner or Hatt-Turner impact-testing machine is generally used with progressive heights of drop, its most common adaptation being in the testing of small timber beams as outlined in A.S.T.M. Designation D143-27, Art. 64. Graphical records of deflections may be secured on a rotating drum.

The Page toughness-testing machine for small specimens of rock is based on the same principle as the Hatt-Turner machine. Its operation is described in A.S.T.M. Designation D3-18. In the days of horse-drawn steel-tired traffic the toughness test for rock was considered quite important and significant for stone to be used in macadamized roads.

The A.S.T.M. has specifications for Drop Shatter Tests for Coal and Coke (Designations D440-37T and D141-23). Tests of the Charpy and Izod types (Designation D256-41) are used on electrical insulating materials in a manner similar to their use for metals as covered by A.S.T.M. Designation E23-41T and discussed subsequently.

Random samples of steel rails are sometimes tested for impact resistance by means of drop tests, the full-size rail being dropped as a falling beam upon a metal tup.

The impact resistance of metallic materials is usually measured by the Charpy test or the Izod test. Each of these tests requires a standard specimen having an accurately formed notch. The energy required to break the specimen is provided by releasing a pendulum from a known height. The specimen is supported as a beam at the bottom of the arc described by the pendulum. When the pendulum is released it swings down, breaks the specimen, and rises on the opposite side. The height to which the pendulum rises indicates the residual energy in the pendulum, and from that the energy required to break the specimen may be approximated closely. However, little is known relative to the distribution of the energy throughout the specimen. When tested by this method, specimens of the same material and of similar geometric proportions, but of different sizes, will not give equal values for the modulus of toughness (energy per cubic inch of specimen). Therefore,

one must recognize that such tests supply only an index of toughness rather than a measure of toughness as a property of the material.

The Charpy and Izod indexes of toughness are especially useful as aids to control in manufacturing processes where the duplication of different alloys and heat treatments are involved. They are used extensively in certain industries.

The Charpy test uses a specimen mounted as a simple beam, while in the Izod test the specimen is mounted as a cantilever. In each test the specimen is placed in such a way that the root of the notch is in tension. The detailed dimensions of the specimens are given in A.S.T.M. Designation E23-41T.

74. References on Fatigue and Impact.

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SUPPLEMENTARY QUESTIONS

247. What property of a material constitutes a measure of its resistance to elastic impact?

248. Should the modulus of toughness as evaluated by any of the usual methods, such as the area under the stress-strain diagram for a static tensile test or from an actual application of energy loading, be expected to equal the maximum concentration of energy within the specimen per unit volume of the material? Explain.

249. Indicate whether each of the following statements is true or false, giving the reason for your answer.

- a. The work of rupture per unit volume or modulus of toughness for a tensile specimen of ductile steel tested on a 2-in. gage length is a more correct measure of the maximum impact resistance of the material than is the value determined from test on an 8-in. gage length.
- b. The energy per unit volume required to fracture a sizable block of stone gives a more correct indication of the ultimate impact resistance of the material than does the unit energy required to pulverize a small fragment of identical quality.
- c. A notched beam should be able to resist a greater flexural impact load than an unnotched beam with a cross section the same as that of the notched beam
 - (1) At the notch.
 - (2) Along the unnotched portion.

250. a. Why may strong steel crack, as does glass or china, when tapped with a steel hammer?

b. Can hard steel be hammered without danger of cracking it?

251. a. Discuss what happens when an anvil is struck with a sledge hammer.

b. If the anvil rests on a pair of scales, are these likely to be damaged by a sharp blow on the anvil?

c. On what will the amount of momentary increase in the scale reading depend?

d. What happens to the energy?

e. What happens to the momentum of the moving hammer?

f. If the hammer is simply pushed downward on the anvil, will the scale reaction be influenced?

252. Does vibration resemble impact?

253. a. Does vibration (considered here to be a form of impact) ever prove to be a useful engineering tool or phenomenon?

b. What are some of the objectionable aspects of vibration?

c. In the design of engineering machines and structures how may the harmful effects from ordinary impact be minimized?

d. What additional measures are helpful if the vibration, some of which probably accompanies all impact, is pronounced?

e. Give an illustration of fluid impact.

f. Indicate the means used to minimize the amount of the impact and the harmful effects from water hammer in a pipe line.

254. Explain:

a. Doubling the length of a bar of given diameter doubles its resistance to axial impact.

b. The impact resistance of an axially loaded bar with a short length of reduced cross section will be increased if the reduced cross section is extended to include the full loaded length of bar.

c. The impact resistance of a bolt can be increased by turning the entire bolt down to a diameter equal to that at the base of the threads.

d. The impact resistance of a beam or a shaft is only a fraction of the product of its volume and the modulus of toughness of the material.

e. In spite of its brittleness a mass of reasonably strong concrete is difficult to break up by the "sledge-hammer method."

f. In spite of its strength a piece of strong steel is likely to be cracked by a light blow with a steel hammer.

g. A bullet may be shot through a pane of glass without producing general fracture.

h. A tallow candle can be shot through a plank.

i. A bullet or a rock can glance from a water surface rather than penetrate it.

j. A suddenly applied load should produce a maximum intensity of stress twice that produced by a gradually applied load if the maximum stress does not exceed the proportional limit.

255. a. Name the impact tests found among the current A.S.T.M. Standards and indicate

- whether each is of the "single-blow" or the "progressive" type.
- b. What information can be gained from the "progressive" type of test which is not available from the "single-blow" type?
 - c. What is an important disadvantage of the progressive type of test?
- 256.** Name one or more other impact tests which are sometimes used in the field of materials.
- 257.** Different grades of steel may be used as reinforcement for concrete. Railroad and highway engineers have sometimes contended that rather ductile grades should be used for highway and railway bridges on account of the possible impact hazard from the live loads that these structures carry.
- a. Does that appear to be a valid contention? Explain.
 - b. Are there any published results of experimental studies of such impact?
 - c. Does the use of harder grades of steel introduce any added job problem?
- 258.** a. What should the theoretical impact stress allowance be for a member to which the load was applied instantaneously but without vertical height of fall before coming in contact with the member?
- b. In designing railway and highway bridges, it is customary to increase the load assumed as the basis for design by some arbitrary amount, such as 10, 25, or 50 per cent, as a so-called *allowance for impact*. Do such percentages appear to be of about the proper order for the live-load conditions that exist for a bridge?
 - c. For which structure should the greater impact allowance be made, a railway bridge or a highway bridge?
 - d. Does the type of bridge (suspension, riveted truss, etc.) have an important bearing upon its impact resistance?
 - e. As a structural unit should the highway pavement slab be designed for static loading, for impact loading, or for fatigue?
- 259.** a. Why is the evaluation of endurance limit less simple than that of other properties which involve stress?
- b. What gave rise to the belief that repeated stress caused members to "crystallize"?
 - c. Why do the moving parts of high-speed machinery which are subjected to repeated loading need to have an exceptionally smooth finish?
 - d. Is repeated impact loading more serious or less serious than is repeated static loading of comparable maximum stress intensity? Explain.
- 260.** Explain what is meant by each of the following terms and indicate the relationship of each to fatigue:
- a. Stress raiser.
 - b. Shatter crack (in a railroad rail).
 - c. Transverse fissure (in a railroad rail).
 - d. Corrosion fatigue.
 - e. Reversed bending.
 - f. Crystallization.
 - g. Fatigue strength.
 - h. Endurance limit.
- 261.** Does plain concrete have an endurance limit?
- 262.** A piece of wire can be broken by bending it back and forth a few times.
- a. Is this a manifestation of fatigue?
 - b. How do you explain the small number of stress repetitions that are required to produce failure?
- 263.** Often the cross section of a member that has failed by fatigue shows a shiny worn portion and a central portion that resembles a static fracture. Explain.
- 264.** Compare the relative importance of fatigue with respect to the loading conditions of a railway bridge and a steam turbine.
- 265.** a. Is the endurance limit of a material likely to be higher or lower than its proportional limit?
- b. Is there any apparent reason why this should be so?

PROBLEM 15

Standard Impact Test of Metal

A. Object.—To study a pendulum-type impact testing machine and to perform a standard notched-bar impact test.

B. Specimens.—Standard notched-beam impact specimens.

C. Special Apparatus.—Charpy or Izod impact machine.

D. References.—Articles 72–73. A.S.T.M. Designation E23–41T.

E. Determinations to Be Made.

1. The initial energy of the blow.
2. The total energy absorbed by the specimen.
3. The velocity of the pendulum at the instant of impact.

F. Procedure.

1. *Preparation for the Test.*—Level the machine, and let the pendulum come to rest at the lower end of its swing. Adjust the striking edge, if necessary, so that it will be on a vertical line through the center of rotation. Before the specimen is inserted, release the pendulum, observe the reading at the end of its swing, and again after a complete oscillation.⁴ Check the loss in energy in the oscillation against the A.S.T.M. requirements.

With the pendulum swinging through an angle of not more than 15 deg. take data to determine the time required for a complete oscillation. Measure the distance from the center of rotation of the pendulum to the striking edge.

2. *Performance of the Test.*—Insert the specimen in the supports in such a way that the notch will be in tension. If the Izod test is being performed, be sure that the specimen is clamped securely. Release the pendulum, and observe its residual

⁴ If the machine is equipped with a brake for retarding the return swing, the brake must be released temporarily to allow a free swing of the pendulum.

energy after breaking the specimen. Repeat for the other specimens to be tested.

G. Report.—Compute the percentage loss in energy for one oscillation of the pendulum. Compute the distance from the axis of rotation of the pendulum to the center of percussion, using the formula $l = 0.81p^2$, in which l = distance (in feet) and p = time required for one complete oscillation (in seconds), and compare with the distance from the axis to the striking edge.

Tabulate the determinations for each specimen. Compare the total energy absorbed by each specimen with the product of the volume and the modulus of toughness in tension, if values for the modulus of toughness are available.

H. Supplementary Questions.

266. Define center of percussion.

267. Derive the formula given for locating the center of percussion.

268. Approximately how will the distribution of energy throughout the specimen vary just prior to failure?

269. Why is the energy required to break the specimen less than that computed by multiplying the modulus of toughness by the volume?

270. How would you expect variation in radius of curvature of notch to affect the toughness index given by this test?

271. Why should the notch be in tension?

PROBLEM 16**Impact Test of a Timber Beam**

A. Object.—To observe the behavior of a timber beam under an impact load, and to evaluate its resistance to failure.

B. Specimen.—Nominal 2-in. by 2-in. by 6-ft. timber beam.

C. Special Apparatus.—Loaded hanger which may be dropped onto the beam from different heights, and facilities for measuring the deflections autographically.

D. References.—Articles 72–73. Chapters on impact in beams in textbooks on mechanics of materials.

E. Determinations to Be Made.

1. Deflection graph of the beam for each loading.
2. Energy of the last load that was applied prior to fracture.

F. Procedure.

1. *Preparation for the Test.*—Determine the dimensions of the beam and attach it in the end

fixtures so that it is free to rotate but cannot bounce from the supports. Attach a pencil at mid-span so that it will trace a record of the deflection on the record sheet as it is moved along the reference bar. Compute the approximate height from which the 50-lb. (or other value given by the instructor) weight must be dropped to produce a maximum stress of 10,000 p.s.i. in the timber.

2. *Performance of the Test.*—Apply the load slowly to obtain a reading for the deflection under the condition of steady loading. Raise the load to one-fourth of the computed height, and release it. At the same time move the record sheet at a uniform rate so that the pencil will trace the deflection-time curve for the center of the beam. Repeat, increasing the height of drop the same amount each time, until the beam fractures.

G. Report.

1. *Graph Sheet.*—Plot the total drops (heights of drop plus maximum deflections) as ordinates

against the corresponding maximum deflections as abscissas.

2. *Results.*—Determine the modulus of elasticity of the timber from the deflection measured during the static loading. From the measured deflection calculate the equivalent static load corresponding to each of the impact loads, assuming load and deflection to be proportional. Calculate the theoretical deflection corresponding to each of the impact loads by equating the work done by the impact load to the work done by the equivalent static load, and plot the results on the graph sheet to the same axes as were used in plotting the experimental result.

Compute the total energy of the last load which the beam sustained prior to failure.

H. Supplementary Questions.

272. Can the proportional limit of the material be determined from this test?

273. Can the modulus of resilience be determined from the deflection data?

274. What is meant by the equivalent static load?

275. Why is the total energy required to break the beam not equal to the modulus of toughness of the material multiplied by the volume of the beam? Explain.

276. Had failure been attained by a single blow or drop, as in the Charpy or Izod test, should the energy required for failure have been more or less than that at which the beam failed?

277. Why is timber unusually well suited for service where repeated impact is present?

PROBLEM 17

Endurance Test of Metal

A. Object.—To determine the endurance limit of a metal and to compare it with some of the properties evaluated by a short-time test.

B. Specimens.—Eight or more companion specimens of metal.

C. Special Apparatus.—One or more fatigue machines.⁵ Extensometer.

D. Reference.—Articles 68–71.

E. Determinations to Be Made.

1. Elastic strength.
 - a. Proportional limit.
 - b. Johnson's apparent elastic limit.
 - c. Yield strength.
2. Ultimate tensile strength.
3. Endurance limit.
4. Ratio of endurance limit to ultimate strength.
5. Ratios of endurance limit to the criteria of elastic strength.

F. Procedure.

1. *Preparation for the Test.*—Perform a tensile test on one of the specimens to determine the elastic strength and ultimate strength as outlined in Probs. 4 and 5. Determine the magnitude of the repeated load which will cause a stress less than the ultimate by an amount equal to approximately one-fourth of the difference between the ultimate strength and the elastic strength.

2. *Performance of the Test.*—Place the specimen

⁵ With the procedure outlined, one machine operating at 1800 cycles per minute will permit the evaluation of the endurance limit of one material in about 6 weeks.

in the machine and apply the computed load. Set the revolution counter to zero and start the machine. After the specimen has broken, remove the pieces, and record the reading of the revolution counter. Place another specimen in the machine, and apply load sufficient to produce the next smaller stress (less than the preceding stress by an amount approximately one-fourth the difference between the ultimate and elastic strengths). Repeat until all the specimens are fractured, or until one has withstood approximately fifty million repetitions of stress.

G. Report.

1. *Graph Sheet.*—In the lower half of the sheet plot the stress-strain diagram for the standard tensile test. In the upper half of the sheet plot an *S-N* diagram for the test, *i.e.*, the applied stress for each of the specimens as ordinates against the logarithms of the number of cycles required to produce failure.

2. *Results.*—Tabulate the properties listed and compare with accepted values.

H. Supplementary Questions.

278. a. For what metals is the endurance limit a well-defined quantity?
- b. For what metals is it a poorly defined quantity?
- c. For such materials what procedure may be followed in evaluating a usable so-called *endurance limit* that can be considered suitable for design use?

279. In general, how does the value for endurance limit as obtained from an axially stressed specimen compare with the limit as obtained from a rotating-beam specimen?

280. What effect may the speed of rotation of a rotating-beam specimen be expected to have upon the value found for the endurance limit?

281. Did any of the fractured specimens appear to have failed progressively from a scratch or other surface roughness?

282. At an average of 50 cars per hour and of two axles per car, how many months of highway traffic would be required to produce 50,000,000 applications of stress on a pavement slab?

CHAPTER XI

DESIGN, CONTROL, AND CURING OF CONCRETE MIXTURES

BASIC CONSIDERATIONS

75. Introduction.—Service constitutes the ultimate test of any structural material, and in this regard concrete is not unique. Concrete does differ from the other primary structural materials, however, in the extent to which the quality of the ultimate product may be altered by conditions and operations which are linked to the job rather than to manufacturing processes. Although the cement, aggregates, and reinforcing steel can be specified and inspected prior to use, the properties of the concrete are largely determined by the design or adjustment of the proportions of material in the concrete, the placement of reinforcing steel and concrete, and the subsequent care of the concrete.

The design of a concrete mixture consists in the determination of the proportions and quantities of cement, aggregate, and water which will produce a unit volume of placeable concrete capable of developing desired characteristics.

The properties of hardened concrete which are normally considered to be of primary importance are (1) strength, (2) durability, (3) appearance, and (4) economy. Properties such as volume change, heat of hydration, impermeability, and resistance to unusual types of exposure may be controlling factors in some applications. These are, for the most part, special aspects of durability.

The objective in concrete construction is to produce concrete of predetermined quality and of good appearance at minimum cost. To attain this objective, it is necessary that the engineer

a. Determine and specify the minimum permissible values of the properties which the hardened concrete must have in order to meet the requirements of the given job.

b. Determine or select criteria by which the properties specified in *a* can be related to the properties and proportions of the materials from which the concrete will be manufactured.

c. Evolve or select an orderly technique of design whereby the criteria of *b* may be applied to meet the requirements as set forth in *a*.

d. Maintain at every stage of the manufacturing process the control which is essential for the production of uniform concrete of proper potential quality.

e. Provide such subsequent treatment and care as will result in the attainment of concrete of the quality desired.

76. Discussion of the Steps Involved.

a. Specifying the Requirements.—As has already been stated, the essential characteristics of concrete are generally considered to be strength, durability, appearance, and economy. These are all relative terms, and strength, durability, appearance, and economy which are adequate for one use may be wholly inadequate for another.

1. **STRENGTH** is a definite property for which tests can be made according to a well-standardized technique. The term strength (without further qualification), as applied to concrete, refers to the 28-day ultimate compressive strength of specimens which have been cured under standard conditions (one day in the mold under moist cover and 27 days continuously moist, or wet, at approximately 70 F.) (see A.S.T.M. Designation C39-39).

2. **DURABILITY** is a general term which may depend upon resistance to weathering, volume change, abrasion, chemical attack, impact, fatigue, or a variety of other factors which contribute to deterioration or to gradual breakdown. While freezing and thawing tests and various accelerated tests have been employed for evaluating certain aspects of durability, it is not surprising that there is no accepted or standardized measure of this property. Fortunately, in most (but not all) of its manifestations, the property of durability more or less parallels that of strength, and any factor which adds to the strength of concrete, may in most instances, be accepted as also adding to its durability. For the usual purposes of design, therefore, the strength which is specified represents the strength which is deemed essential for durability as well as for resisting load.¹

¹ An alternative, sometimes employed with requirements for durability in view, is to specify not only a minimum of strength but also a minimum cement content and sometimes a maximum water content.

3. **APPEARANCE** adequate for many situations requires nothing beyond good forming and proper placement of workable concrete. For other situations special surface treatments are becoming increasingly important. Sometimes durability is as important in its relationship to appearance as it is to the other aspects of serviceability.

4. **ECONOMY** relates to the relative cost of the concrete in place. In many cases the differences in the cost of alternative mixtures will be secondary to other items. When economy is a determining consideration, the decision will usually hinge upon the relative cement requirement. In some cases, however, relative cost of the aggregates or of placement may be a dominant factor.

b. Criteria for Predicting Quality of the Hardened Concrete. 1. **STRENGTH**.—Within the usual range of workable mixtures, the strength of concrete may be assumed to vary inversely as the *water-cement ratio* or directly as the *cement-water ratio*. Figure 20 shows the nominal relationship which exists between these ratios and the strength for current concretes made from approved aggregate and portland cement of Type I (A.S.T.M. Designation C150-41T).²

TABLE V.—CONVERSION FACTORS FOR WATER-CEMENT RATIOS

(Note that cement-water ratios are simply the reciprocals of the corresponding water-cement ratios)

Line	Units in common use	Water-cement ratios			
		Gal. per bag, a common job unit	Absolute volume (approx. <i>v/c</i> Talbot)	Loose volume (original Abrams unit)	Weight (job and laboratory)
		(a)	(b)	(c)	(d)
1	<i>w/c</i> gal. per bag	1	0.279	0.134	0.089
2	<i>w/c</i> abs. vol.	3.58	1	0.479	0.318
3	<i>w/c</i> loose vol.	7.48	2.09	1	0.664
4	<i>w/c</i> weight	11.3	3.15	1.51	1

Table computed on the basis of the following assumed constants or unit values. Bold-faced figures are basic assumptions. Light-faced figures are computed from the values assumed.

1 cu. ft. water weighs 62.4 lb. and contains 7.48 gal. 1 gal. water weighs 8.34 lb. **1 cu. ft. cement loose (as sacked) weighs 94.0 lb. = 1 bag = $\frac{1}{4}$ bbl. and contains 0.478 cu. ft.**

² See discussion of Questions 289 and 290 for a consideration of the limitations of the water-cement ratio and of the voids-cement ratio as criteria for strength of concrete.

of solid particles. **Specific gravity of cement = 3.15.** 1 cu. ft. cement (solid) weighs 196.6 lb. and contains 2.09 bags or 2.09 cu. ft. loose (in bulk as sacked).

Use of Table.—All values along any horizontal line are equivalent to one another.

Examples.—*a.* To determine the number of gallons per bag which corresponds to *w/c* by weight of 0.70. On line 4, Col. (a) and (d), *w/c* of 1.0 by weight = 11.3 gal. per bag. Then *w/c* of 0.70 by weight = $(0.70)(11.3) = 7.91$ gal. per bag.

b. To determine the number of gallons per bag corresponding to *c/w* of 0.50 by absolute volume. *c/w* of 0.50 = *w/c* of 2.00 by absolute volume. On line 2, Col. (a) and (b), *w/c* of 1 by absolute volume = 3.58 gal. per bag. Then *w/c* of 2 by absolute volume = $(2)(3.58) = 7.16$ gal. per bag.

Discussion of Units for w/c and c/w.

a. w/c in gallons per bag. Much used as basis for job measurements. Water measuring tanks on concrete mixers may be calibrated in gallons. After a concrete mixture has been designed, the water requirement may need to be converted to gallons per bag of cement.

b. w/c by absolute volume. As a ratio this quantity is not used. If, however, the voids in the concrete are assumed to consist of the mixing water (air voids disregarded), then *w/c* becomes essentially *v/c*, the voids-cement ratio used by Talbot and Richart as the criterion for strength in the basic mortar-voids method of designing and controlling concrete mixtures.

c. w/c by loose volume. This is the measure used by Abrams when he first expounded his water-cement-ratio strength-relationship about 1918, and for that reason the measure became rather firmly established in this country. For the conditions of present concrete design and practice, loose volume is not a logical basis for expressing water-cement ratio, and it will probably become less important as time advances. By "loose volume," as applied to the cement, is meant the bulk volume of the cement as sacked. Cement is sacked by weight in sacks of 1 cu. ft. nominal volume, 94 lb. of cement to the sack. The nature of cement is such that the actual loose volume may vary greatly depending upon the extent of "fluffing up" from entrapped air. Water has no "loose volume" as distinguished from its *absolute volume*.

d. w/c by weight. This is a ratio of weight to weight and is, therefore, without units. It is a basic measure and means the same thing in metric units as it does in English, *i.e.*, pound/pound = kilogram/kilogram = gram/gram, etc. Weight has always been the basis for controlled laboratory measurements of materials and is becoming ever more widely used as the basis for job measurements.

Cement-water Ratios vs. Water-cement Ratios.—While cement-water ratios are simply the reciprocals of the water-cement ratios, they are coming rather generally into use partially because strengths vary directly instead of inversely as the ratio. Another advantage is that the line for *c/w* vs. strength is nearly straight whereas that for *w/c* vs. strength is very much a curve.

As a safeguard it will generally be well to check conversions against the plotted scales of Fig. 20. For field purposes the plotted scales can, in fact, be read with sufficient accuracy for most of the conversions that need to be made.

Table V supplies convenient conversion factors between the various units in which the water-cement ratio (w/c) or cement-water ratio (c/w) may be expressed.

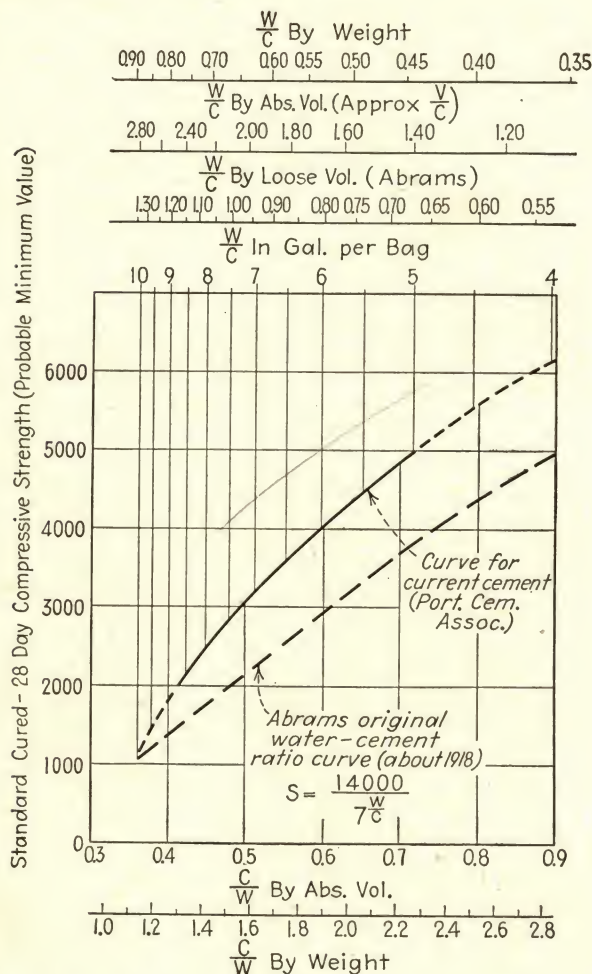


FIG. 20.—Strength vs. $\frac{C}{W}$ and $\frac{W}{C}$ (various units).

2. DURABILITY. As previously indicated durability is assumed to vary with the strength. On the basis of this assumption the water-cement ratio is adopted as the criterion for both strength and durability. Durability, therefore, enters the design picture only indirectly.

3. APPEARANCE. The appearance of the hardened concrete depends on (a) the workability of the concrete at the time of placement, (b) the method of placement, (c) the nature of the form, and (d) the finishing operation on the surface.

(a) Workability, while not a property of the hardened concrete, is a means to an end in that the concrete can be strong, durable, of good appearance, and economical only

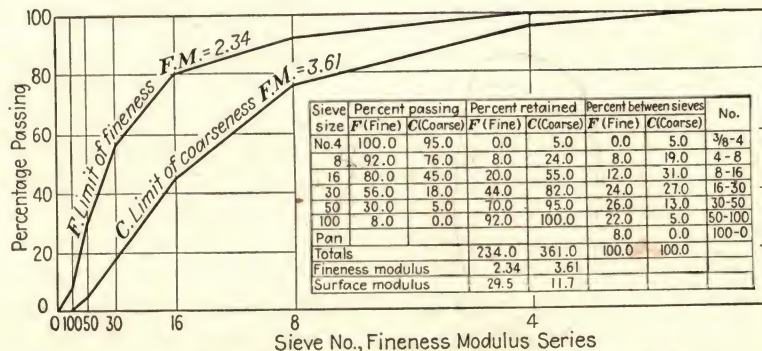
if the workability is right for the existing conditions of placement. Workability as a property of freshly mixed concrete embodies (1) consistency or stiffness and (2) texture.

The consistency is measured almost universally by the slump test (A.S.T.M. Designation C143-39). The flow-table test (A.S.T.M. Designation C124-39) is a supplementary test of consistency, often used in the laboratory but rarely used in the field. Within the range of properly graded mixtures consistency depends mainly upon the relative water content. The texture of a concrete mixture is observed rather than measured and may be described as harsh (undersanded), plastic (workable), or fat (rich in cement or oversanded). For a given type of aggregate and a given cement content, texture is a function of the grading.

- (b) Good placement is essential to good appearance. Methods must be such as to insure freedom from visible porosity, stone pockets, or honeycombing if stiff or harsh mixtures are used; and freedom from segregation, laitance, and sand-streaking if the mixtures are of low consistency (high slump or overly wet). From the standpoint of appearance, spading near the faces of the forms is usually important in addition to the spreading, stirring, tamping, and vibrating appropriate to different mixtures and situations.
- (c) Good forming is indispensable to good appearance. The forms must be of suitable surface texture, accurately dimensioned, well aligned, and properly braced and joined.
- (d) The surface finish usually involves only rubbing or grinding off form marks and the repair of surface defects. To an increasing extent decorative and semi-decorative concretes are accorded post-casting treatment in the form of extensive grinding, sandblasting, treatment with dilute acids or even painting to produce special desired surface colors or textures or to expose special aggregates placed in the surface concrete. Terrazzo floors constitute a long-standing example of the ground-surface type of finish.

4. ECONOMY. Economy is usually determined on the basis of the relative amount of cement required to produce a concrete of the specified

The grading of an aggregate refers to the relative amounts of the different size groupings constituting the aggregate.

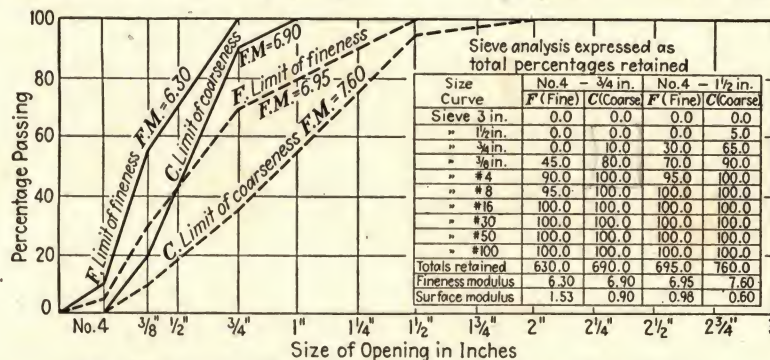


(See A.S.T.M. Designation E11-39 for Data on Size of Openings, etc.)

FIG. 21.—1940 Joint Committee grading limits for fine aggregates (0—No. 4). The grading limits conform essentially to those specified in A. S. T. M. Designation C33-40.

workability and quality. A decrease in the cement requirement lowers the cost, thereby increasing the economy. The factors which exercise the greatest influence upon the cement requirement, aside from the fineness and other characteristics inherent in the cement, are (a) the maximum size and grading of

Knowledge and control of the grading are important, since for an aggregate of a given maximum size the amount of cement required to produce concrete of a specified strength and workability decreases with excellence of grading.³ The grading of



(See A.S.T.M. Designation E11-39) (Solid Lines are Sieves of Fineness Modulus Series)

FIG. 22.—1940 Joint Committee grading limits for coarse aggregates of two maximum sizes, No. 4—3/4 in., No. 4—1 1/2 in. The grading limits conform essentially to those given in A. S. T. M. Designation C33-40.

the aggregate and (b) the workability required for the particular conditions of placement.

(a) The larger the maximum size of a graded aggregate that can be used, the lower will be the amount of cement required to produce a concrete of a given quality (see Figs. 27 and 28). Established practice generally limits the maximum size of aggregate to one-fourth of the least dimension of the form. The aggregate must also pass easily between reinforcing bars, and it must not be too large for proper handling by the batching, mixing, and placing equipment used.

aggregate is determined from sieve-analysis data (A.S.T.M. Designation C136-39) obtained by screening a sample of the aggregate through a series of standard sieves.⁴ The weight of material retained on each sieve is determined, from which the results may be expressed as percentages retained on each sieve or as cumulative percentages either passing or retained

³ In general, excellence of grading implies an assortment of sizes favorable to close packing of particles, resulting in an assemblage of low void content.

⁴ The sizes of sieve openings, tolerances, and wire diameters are given in A.S.T.M. Designation E11-39, Standard Specifications for Sieves for Testing Purposes.

on sieves. Figures 21 and 22 show sieve-analysis data for fine and coarse aggregates tabulated in all three ways and plotted as

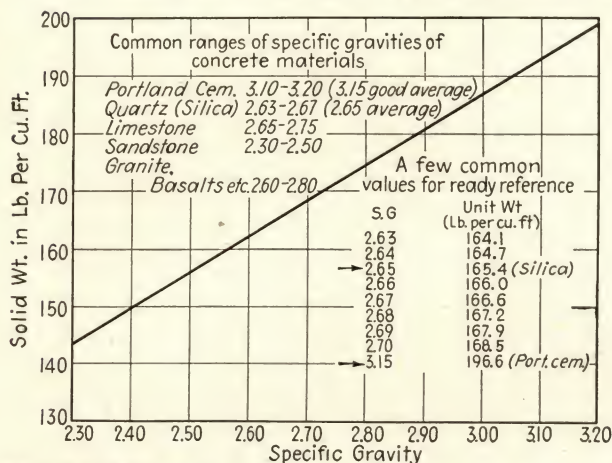


FIG. 23.—Solid weights per cubic foot corresponding to various specific gravities.

total percentages passing sieves with successively larger openings. The *fineness modulus* is a commonly used grading index which may be defined as the cumulative sum of the weights of the material retained on the sieves of the fineness-modulus series⁵ divided by the total weight of the sample.

For research purposes or for important work of considerable magnitude, aggregate may be separated into two or more grading ranges and recombined to produce or to maintain some predetermined grading, but on the average job the only attempt at control of grading is the maintenance of the specified limiting sizes of fine and coarse aggregate, respectively. The grading of "total aggregate" for given fine and coarse aggregates varies with the relative proportions of fine and coarse aggregate which are selected.

- (b) Workability is closely related to economy. Generally speaking, the stiffest and hardest concrete of placeable consistency that can be obtained from given aggregates has the lowest cement content and is, therefore, the most economical concrete. Beyond sufficient workability for adequate

⁵ The fineness-modulus series of sieves are the Nos. 100, 50 (or 48), 30 (or 28), 14 (or 16), 8, 4, $\frac{3}{8}$ in., $1\frac{1}{2}$ in., 3 in., etc., in which the linear dimension of each successive opening is double that of the preceding one (see A.S.T.M. Designation E11-39).

placement, added workability is secured only at the expense of some decrease in economy. The addition of aggregate lowers the cement factor, but it stiffens and harshens the mixture. As previously mentioned, the grading, workability, appearance, and economy are all closely linked to one another, and a suitable design of any mixture necessitates a proper balancing of these factors.

c. Design Technique.—Since strength, durability, and appearance reduce for design purposes to strength and workability, the design of a concrete mixture consists essentially in determining (1) the relative proportions and (2) the quantities of aggregate, cement, and water which will produce at reasonable cost a concrete of the necessary strength and desired workability. While a number of techniques have been developed, the water-cement-ratio trial-batch method lends itself unusually well to the conditions of current practice and has been selected as the basis for the detailed study accorded to the design of mixtures in Prob. 18. Within the range of usual mixtures, strengths can be predicted closely on the basis of the water-cement-ratio criterion, but there is no satisfactory analytical criterion for a close predetermination of workability. Measurable characteristics of the aggregate provide, at best, only crude indications of probable workabilities. To predict workabilities with assurance, it is necessary to mix up one or more batches for the measurement of consistency and the observation of texture.⁶ The detailed technique is outlined in Prob. 18.

As soon as the proportions or relative amounts of the several constituents have been ascertained, it is necessary to establish relationships which will enable the engineer to determine how much of each constituent is required to produce a specified volume of concrete in place. The sum of the volumes of the materials which make up a unit volume of concrete in place, occupies more than a unit volume when the materials are measured separately in bulk. Thus, as shown on Line 40 of the tabular material beneath Fig. 26, about 43 cu. ft. or 1.6 cu. yd. bulk volume of cement, fine

⁶ If trial-batch data are available for the same materials at the desired workability, but for a mixture of different strength, the proportions for a concrete of the desired strength may be determined without repeating the trial-batch operation by application of the Lyse technique as explained subsequently. The Lyse technique is also useful for adjusting proportions at constant workability.

aggregate, coarse aggregate, and water (about 1.4 cu. yd. exclusive of the water) is required to produce 1 cu. yd. of those concretes. On the other hand,

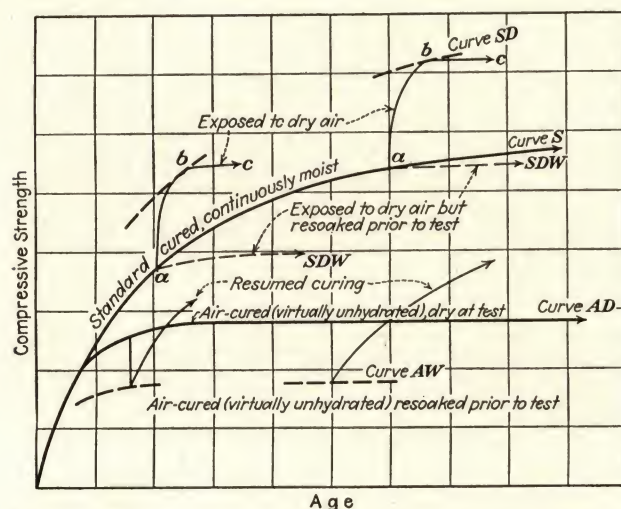


FIG. 24.—Effects of curing and test conditions upon compressive strength of normal portland cement mixtures.

the absolute or solid volume (that which the material would displace in a liquid) of each of the constituents is the same in the concrete as it is in bin, stockpile, or bag. The simplest procedure for reducing the required proportions of a mixture to quantities susceptible of separate measurement is to determine from the trial-batch weights the absolute-volume proportions of cement, aggregate, and water in a unit volume of concrete. These absolute-volume proportions are converted to the weights required to produce a unit (or other designated) volume of concrete. The weights may in turn be converted to bulk-volume units if materials are to be measured rather than weighed. The details of these computations are covered in the illustrative calculations of Art. 79.

When the possible choice lies between several aggregates or gradings, the final decisions are usually reached on the basis of comparisons of cost in place of different mixtures, all of which meet the requirements of strength, workability, and probable appearance. The “yield” or the “cement factor” (see definitions) is usually, but not always, the governing criterion for cost. The statement of the proportions and of the quantity of each material required to produce a cubic yard (or other definite quantity of concrete in place) normally completes the design of the mixture.

d. Manufacture and Fabrication.—The actual operations of construction should be carried out in accordance with the specifications for the work and

the tenets of good concrete practice. This includes making adequate provision for accurate measurement of materials for the batches, and adequate

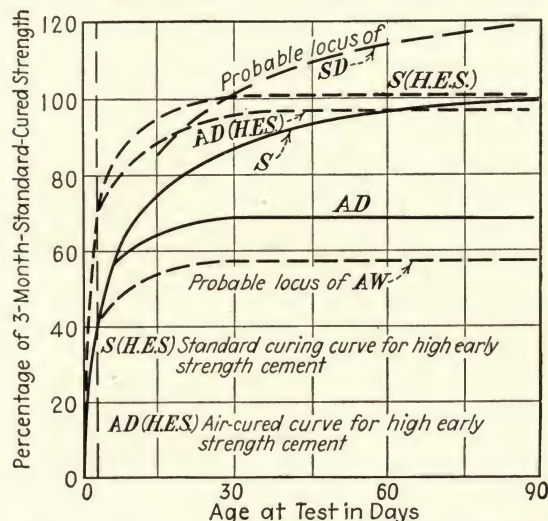


FIG. 25.—Comparative curing curves for normal and high early-strength portland cement concrete.

mixing, transportation, and placement without segregation or honeycombing. It also includes suitable provision for inspection and the securing of representative samples at intervals as the work progresses.

e. Subsequent Treatment.—Even if properly designed and placed, a concrete can develop its potential strength only if kept at a favorable temperature and adequately supplied with water for hydration. Figures 24 and 25 show the role that moisture plays in influencing the strength of a normal and of a high-early-strength portland-cement concrete.

SUPPLEMENTARY CONSIDERATIONS

77. Adjustments to Meet Field Conditions.—Steps *d* and *e* are likely not to be so simple as has just been implied because of various practical conditions that complicate the measurements of materials on a job and for which corrections must usually be made as the work progresses. The most common of these factors are

a. Nonuniformity in the grading of the aggregates, *i.e.*, concentrations of fine and coarse particles. This may result from methods of storing or handling that tend to produce segregation or size separation, or it may be because of a source that does not yield a uniform product.

b. Use of dry aggregates which absorb a portion of the mixing water, thereby decreasing the net or effective water-cement ratio of the concrete and

stiffening the mixture, thus lowering the workability from that for which the mixture was designed.

c. Presence of free moisture in the aggregate which, for weighed batches, adds to the amount of water and subtracts from the amount of aggregate in the batch, thereby lowering the strength and altering the workability.

d. Presence of free moisture in the fine aggregate accompanied by "bulking."⁷ For volumetric batching, correction must be made for the decreased amount of sand occupying a given volume as well as for the free moisture which the sand contains.

Controlling the uniformity of the grading is a problem which may call for differences in methods of handling, separation into size classes, etc., and will not be considered here.

Dry, absorptive aggregates are not usual since most stock piles contain sufficient moisture to saturate the aggregate even if there is not an excess of free moisture on the surfaces of particles for which corrections need to be applied. The ideal condition for an aggregate is that it be surface dry and saturated, or at least that it contain enough moisture that it will not extract water from the mixture during the period of mixing and placing.

Cases *c* and *d* are frequently encountered to a degree that requires adjustment from hour to hour on the job if the true design proportions of the aggregates and water are to be maintained. Cases *b*, *c*, and *d* are included among the illustrative calculations of Art. 79.

78. Lyse's Method for Extending and Adjusting the Design.—The trial-batch water-cement ratio technique of design normally requires the mixing of a separate trial batch for each different strength of concrete investigated, since, as is apparent from the procedure of Prob. 18, the water-cement ratio is held constant and the quantities of aggregate are varied until the desired workability is attained. As a result of studies on proportioning, Lyse (Reference 1, Art. 89) recognized that it was possible to introduce a simplifying approximation by which the

results from a single trial-batch determination can be extended to cover a wide range of mixtures and strengths of concrete.

Lyse found that within the usual range of mixtures and for any given grading and maximum size of aggregate the strength may be varied at constant workability by the simple expedient of interchanging fine aggregate and cement in equal amounts,⁸ the amounts of coarse aggregate and water being held constant.

Illustrative example 2 demonstrates the simplicity of multiplying or adjusting designs from a single trial-batch determination by use of the Lyse rule. Figure 26 shows graphically how the results from the single trial batch, made at any convenient water-cement ratio, may be extended to cover mixtures all the way from those which are very rich to those which are very lean. Lyse's rule is useful for making adjustments as well as for multiplying designs.

79. Illustrative Calculations Relating to the Design of a Mixture.⁹

Example 1. Design of a Mixture.—To determine by the water-cement-ratio trial-batch method the proportions and quantities of cement, fine aggregate, coarse aggregate, and water to produce a concrete of plastic consistency of about 3 in. slump and a standard 28-day strength of 4000 p.s.i. The materials correspond to those for which properties are listed in Table VI. The aggregates are saturated and surface dry. Compute the following quantities:

- a. The absolute volumes of the constituent materials in 1 cu. ft. of freshly mixed concrete.
- b. The weights of materials in a 1-cu. ft. batch.
- c. Probable weight of the concrete in pounds per cubic foot.
- d. Weights of materials required for 1 cu. yd. of concrete.
- e. Weights required for a one-bag batch of concrete.

⁷ Bulking is a phenomenon characteristic of fine-grained materials. Small percentages of moisture (for sands the amounts for maximum bulking may be from 3 to 10 per cent by weight) fluff or spread the particles and, for a relatively fine sand, may increase its bulk volume by as much as 40 or 50 per cent. The bulking is an intermediate state; material which is inundated (in which all space between particles is filled with moisture) occupies about the same bulk volume as does the same material if the surfaces are entirely dry. Coarse aggregates do not bulk measurably.

⁸ As proposed by Lyse, the interchange was between cement and aggregate. Dunagan (Reference *m*, Art. 89) adopted the simplifying device of holding the coarse aggregate, as well as the water, constant and making the interchange between the cement and the fine aggregate. As a practical matter the "equal amounts" may be either by weight or by absolute volumes since the difference in the relative amount of fine aggregate added or subtracted from the batch will rarely be sufficient to alter visibly the workability.

⁹ A list of terms, definitions, symbols, and algebraic relationships is given in Art. 87 at the end of the chapter.

f. Yield.

g. Quantities by bulk or loose volume for 1 cu. ft. of freshly mixed concrete.

h. Quantities by bulk or loose volume for 1 cu. yd. of freshly mixed concrete.

Solution.—From Fig. 20 it is noted that a 4000 p.s.i. concrete corresponds to a water-cement ratio of 6 gal. of water per bag of cement, which by weight (also from Fig. 20 or Table V) is a water-cement ratio of 0.53.

With this proportion of water and cement a trial batch is prepared in accordance with the detailed instructions of Prob. 18. It is found that the following weights of materials produce a mixture having the slump and texture required.

	Lb.
Cement (amount was chosen arbitrarily)...	6.00
Water (0.53) (wt. of cement).....	3.18
F.A. by trial, see Prob. 18.....	14.74
C.A. by trial, see Prob. 18.....	21.28
Total wt. of batch.....	45.20

Proportions of Cem.:F.A.:C.A. are

6.00:14.74:21.28 or 1:2.46:3.55 by wt.

The absolute or solid volume in cubic feet of each constituent in the batch is determined by dividing the weight of that constituent by the solid weight in pounds per cubic foot (Table VI, Line 6).

$$\text{Abs. vol. Cem.} = \frac{6.00}{196.6} = 0.031$$

$$\text{Abs. vol. F.A.} = \frac{14.74}{165.4} = 0.089$$

$$\text{Abs. vol. C.A.} = \frac{21.28}{165.4} = 0.129$$

$$\text{Abs. vol. water} = \frac{3.18}{62.4} = 0.051$$

$$\text{Abs. vol. batch}^{10} = 0.300$$

One cubic foot of the freshly mixed concrete will contain the following amounts (by absolute volume) of the constituent materials:

¹⁰ This assumes that there are no air voids in the mixture—that all the space occupied by the mixture is filled with Cem., F.A., C.A. or water. Actually some air voids are present, as is shown subsequently, and the mixture occupies a correspondingly greater volume than that shown above.

$$\text{Cem. (c)} = \frac{0.031}{0.300} = 0.102 \text{ cu. ft.}$$

$$\text{F.A. (a)} = \frac{0.089}{0.300} = 0.298 \text{ cu. ft.}$$

$$\text{C.A. (b)} = \frac{0.129}{0.300} = 0.430 \text{ cu. ft.}$$

$$\text{Water (w)} = \frac{0.051}{0.300} = 0.170 \text{ cu. ft.}$$

$$\text{Total} = 1.000 \text{ cu. ft.}$$

The weights of materials in a 1-cu. ft. batch will be as follows:

$$\text{Cem.} = (0.102)(196.6) = 20.05 \text{ lb.}$$

$$\text{F.A.} = (0.298)(165.4) = 49.29 \text{ lb.}$$

$$\text{C.A.} = (0.430)(165.4) = 71.12 \text{ lb.}$$

$$\text{Water} = (0.170)(62.4) = 10.61 \text{ lb.}$$

$$\text{Computed wt., lb. per cu. ft.} = 151.07 \text{ lb.}$$

Quantities required for 1 cu. yd. of concrete in place are as follows:

$$\text{Cem.} = (27)(20.05) = 541 \text{ lb. or } 5.76 \text{ bags} \\ = 1.44 \text{ bbl.}$$

$$\text{F.A.} = (27)(49.29) = 1331 \text{ lb. or } 0.666 \text{ ton}$$

$$\text{C.A.} = (27)(71.12) = 1920 \text{ lb. or } 0.960 \text{ ton}$$

$$\text{Water} = (27)(10.61) = 286 \text{ lb. or } 34.3 \text{ gal.}$$

$$\text{Total wt.} = 4078 \text{ lb.}$$

Quantities by weight required for a one-bag batch of concrete are the proportions by weight times the weight of one bag of cement.

$$\text{Cem.} = (1)(94) = 94.00 \text{ lb.}$$

$$\text{F.A.} = (2.46)(94) = 231.24 \text{ lb.}$$

$$\text{C.A.} = (3.55)(94) = 333.70 \text{ lb.}$$

$$\text{Water} = (0.53)(94) = 49.82 \text{ lb.}$$

$$\text{Total wt.} = 708.76 \text{ lb.}$$

Since the weight of cement in a one-bag batch is 94 lb. and that in a 1-cu. ft. batch is 20.05 lb., the number of cubic feet in a one-bag batch (the yield) = $94/20.05 = 4.69$.

If the measurements of materials for batches are to be by bulk or loose volume instead of by weight, the proportions and quantities are determined as outlined below. From Table VI, Line 10, the loose weights are 94.0, 103.5, and 98.3 lb. per cu. ft. for cement (always as sacked), F.A. and C.A., respectively.

From the weights of the preceding tabulation the quantities for 1 cu. ft. of concrete are as follows:

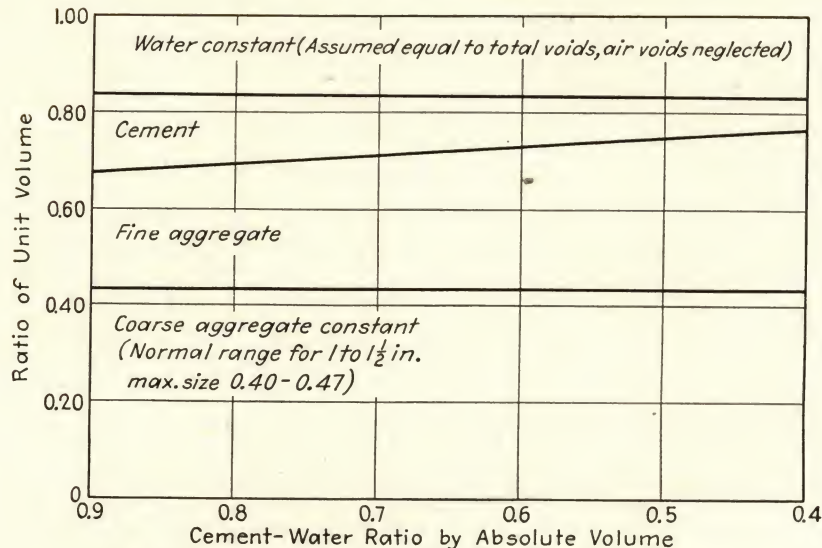


Fig. 26.—Chart illustrating Lyse's method for adjusting designs.

Illustrative terms, properties, conversions and corrections for three mixtures of Fig. 26. (See line 13 for identification.)

1.	Rich	Type of mixture	Medium	From Fig. 20	Lean
2.	4.0	Gal. per bag cem.	6.0	Specified	9.0
3.	6000	Predicted 28-day strength (p.s.i.)	4000	"	1800
4.	3.0	Slump (in.) equal according to Lyse rule	3.0	"	3.0
5.	Plastic	Texture	Plastic	"	Plastic
6.	0.153	Cem. by abs. vol. (no air voids) (c)	0.102	From diagram	0.068
7.	0.247	F.A. " " " " " (a)	0.298	" " "	0.332
8.	0.430	C.A. " " " " " (b)	0.430	" " "	0.430
9.	0.170	Water " " " " " (w)	0.170	" " "	0.170
10.	1.000	Total " " " (t) = (a + b + c + w)	1.000		1.000
11.	1:1.61:2.81	Prop. by abs. vol.	1:2.92:4.22	L 6 to 8 ÷ L 6	1:4.88:6.32
12.	1.61	a/c	2.92	L 7 ÷ L 6	4.88
13.	0.90	c/w " " "	0.60	L 6 ÷ L 9	0.40
14.	1.74	b/a " " "	1.44	L 8 ÷ L 7	1.30
15.	0.70	b/b ₀ " " "	0.70	Line 8 ÷ (Table 6, col. e, line 8)	0.70
16.	30.08	Cem. wt. in 1 cu. ft.	20.05	(c) (196.6)	13.37
17.	40.85	F.A. " " " "	49.29	(a) (165.4)	55.08
18.	71.12	C.A. " " " "	71.12	(b) (165.4)	71.12
19.	10.61	Water " " " "	10.61	(w) (62.4)	10.61
20.	152.66	Total " " " "	151.07		150.18
21.	1:1.36:2.36	Prop. by wt.	1:2.46:3.55	L 16 to 18 ÷ L 16	1:4.12:5.32
22.	3.13	Yield	4.69	94 ÷ wt. cem. in 1 cu. ft.	7.03
23.	812.2	Cem. wt. in 1 cu. yd.	541.4	(27) (Wt. in 1 cu. ft.)	361.0
24.	1103.1	F.A. " " " "	1330.8	" " " " " "	1487.1
25.	1920.3	C.A. " " " "	1920.3	" " " " " "	1920.3
26.	286.4	Water " " " "	286.4	" " " " " "	286.4
27.	4122.0	Total " " " "	4078.9		4054.8
28.	8.64	Bags in 1 cu. yd.	5.76	Wt. ÷ 94	3.84
29.	34.34	Gal.	34.34	Wt. ÷ 8.34	34.34
30.	695	Str.-econ. index (p.s.i./bag cem./cu. yd.)	695	L 3 ÷ L 28	469
31.	94.0	Cem. wt. req'd. for 1-bag batch	94.0	(1)(94)	94.0
32.	127.8	F.A. " " " " " "	231.3	(2.46)(94) from L 21	387.3
33.	221.8	C.A. " " " " " "	333.7	(3.55)(94) " "	500.1
34.	33.4	Water " " " " " "	49.8	(0.53)(94) Convert L 2	75.2
35.	477.0	Total " " " " " "	708.8		1056.6
36.	8.64	Cem. cu. ft. per cu. yd. by loose or bulk vol.	5.76	Wt. ÷ 94	3.84
37.	10.66	F.A. " " " " " "	12.86	Wt. ÷ 103.5 (Table 6, line 10)	14.37
38.	19.54	C.A. " " " " " "	19.54	Wt. ÷ 98.3	19.54
39.	4.59	Water " " " " " "	4.59	Wt. ÷ 62.4	4.59
40.	43.43	Total " " " " " "	42.75		42.34
41.	1:1.24:2.26	Prop. by loose vol.	1:2.23:3.39	L 36 to L 38 ÷ L 36	1:3.74:5.09
42.	0.535	w/c	0.797	Convert L 2, see Table 5	1.195
Illustrative correction. Absorption by the aggregate per cubic yard batch.					
43.	11.03	Absorption F.A. at 1% by wt. (lb.)	13.31	L 24 & Table 6, L 13	14.87
44.	19.20	C.A. " " " " " "	19.20	L 25 & " " " "	19.20
45.	30.23	" correction, add to mixing water	32.51	L 43 and L 44	34.07
46.	+630	" approx. possible effect on str. p.s.i.	+450	Diff. corres. to new w/c	+210
47.	+10.5	" " " " " %	+11.3	(L 46 ÷ L 3) 100	+11.9
48.	*	" effect on slump	*	*Decrease because of less water	*
49.	Negligible	" " " texture	Negligible		Negligible

For remainder of legend see opposite page.

TABLE VI.—ASSUMED DATA ON MATERIALS FOR ILLUSTRATIVE CALCULATIONS

Line	Property (a)	Method of test A.S.T.M. Designation (b)	Material		
			Cement (Cem.) (c)	Fine aggregate (F.A.) (d)	Coarse aggregate (C.A.) (e)
1	Brand or source	.....	Lehigh	Des Moines River	Des Moines River
2	Kind	C150-41	Type I	Sand (washed)	Gravel
3	Size	C136-39	.....	0-4	No. 4—1½ in.
4	Fineness modulus	.....	.....	2.70	7.10
5	Bulk specific gravity	{ C77-40 C127-39 C128-39	3.15	2.65	2.65
6	Solid wt., lb. per cu. ft. (S.G. × 62.4)	.....	196.6	165.4	165.4
7	Compact wt., lb. per cu. ft. (Cem. as sacked)	C29-39	94.0	108.4*	102.0
8	Density (solidity ratio) compact material	.....	0.478	0.657	0.617
9	Voids in compact material	C30-37	0.522	0.343	0.383
10	Loose wt., lb. per cu. ft. (Cem. as sacked)	C29-39	94.0	103.5	98.3
11	Density (solidity ratio) loose material	.....	0.478	0.625	0.594
12	Voids in loose material	C30-37	0.522	0.375	0.406
13	Absorption, per cent by wt.	{ C127-39 C128-39	.....	1.0	1.0
14	Free moisture, per cent by wt.	C70-30	.....	4.0	1.0
15	Bulking, per cent by loose volume*	.....	.....	20.0*	.....

* 20 per cent on basis of bulked volume which would be 25 per cent on basis of dry volume.

Illustrative correction. Free moisture in aggregate per cubic yard batch.

50.	44.1	Free moisture in F.A. at 4% (lb.)	53.2	L 24 & Table 6, L 14	59.5
51.	19.2	" " " C.A. at 1% "	19.2	L 25 & " " "	19.2
52.	63.3	" " " correction, deduct. (lb.)	72.4	{ See illustrative example in text	78.7
53.	44.1	F.A. to be added (lb.)	53.2		59.5
54.	19.2	C.A. to be added (lb.)	19.2		19.2
55.	1:1.36:2.36	Prop. by wt. as designed (sat. surf. dry)	1:2.46:3.55	From L 21	1:4.12:5.32
56.	1:1.41:2.39	" as corrected for free water	1:2.55:3.58	(Apparent)	1:4.28:5.37
57.	1:1.31:2.33	" net if uncorrected	1:2.37:3.52	(Actual)	1:3.96:5.27
58.	-800	Free-moisture approx. effect on strength	-1100	If uncorrected (p.s.i.)	-1250
59.	-13.3	" " " " "	-27.5	%	-71.5
60.	*	" " " " slump	*	*Increase because more water	*
61.	**	" " " " texture	**	**Harsher, decrease in F.A.	**

Illustrative correction. Bulking of fine aggregate per cubic-yard batch. 20 per cent bulked volume or 25 per cent unbulked volume, Table 6, line 15.

62.	2.7	Bulking in F.A. (cu. ft.)	3.2	(0.25) (line 37)	3.6
63.	1:1.24:2.26	Prop. by loose vol. as designed	1:2.23:3.39	From L 41	1:3.74:5.09
64.	1:1.54:2.26	" " " " apparent	1:2.80:3.39	As corrected	1:4.69:5.09
65.	1:0.94:2.26	" " " " actual net	1:1.68:3.39	If uncorrected	1:2.81:5.09

Effect of air voids on quantities, other absolute volume calculations.

66.	147.1	Observed unit wt. (lb. per cu. ft.)	145.3	Assumed	143.6
67.	0.963	Ratio, " " observed to computed (t)	0.962	Line 66 ÷ line 20	0.956
68.	0.147	Cem. (c)	0.098	(Line 67) (line 6)	0.065
69.	0.238	F.A. (a)	0.287	(" ") (" 7)	0.317
70.	0.414	C.A. (b)	0.413	(" ") (" 8)	0.411
71.	0.164	Water (w)	0.164	(" ") (" 9)	0.163
72.	0.037	Air voids (v_a) = $1 - t$	0.038	1—L 67	0.044
73.	1.000	Total for check	1.000		1.000
74.	0.799	Solidity ratio (d)	0.798	$d = a + b + c$	0.793
75.	0.201	Total voids (v)	0.202	$v = 1 - d = v_a + w$	0.207
76.	1.367	Voids-cement ratio (v/c)	2.051	Compare with line 77	3.185
77.	1.116	w/c by abs. vol.	1.673	Line 71 ÷ line 68	2.508
78.	0.422	Cem.-space ratio ($\frac{c}{c+v}$)	0.328	L 68 ÷ (L 68 + L 75)	0.239
79.	0.671	b/b ₀	0.671	Compare with L 15	0.666
80.	0.343	Voids in mortar (v_m)	0.345	$v_m = v ÷ (1 - b)$	0.351
81.	3.25	Yield from observed unit wt.	4.87	Compare with L 22	7.35

Note: In many entries results are indicated to four or five significant figures instead of the three significant figures which are justified by the original data. Since many of the entries are intermediate results this practice is in accordance with the instructions on calculations given in Art. 22. For field use quantities should be rounded off to three significant figures.

$$\begin{aligned}
 \text{Cem.} &= 20.05 \div 94.0 = 0.213 \text{ cu. ft.} \\
 \text{F.A.} &= 49.29 \div 103.5 = 0.476 \text{ cu. ft.} \\
 \text{C.A.} &= 71.12 \div 98.3 = 0.723 \text{ cu. ft.} \\
 \text{Water} &= 10.61 \div 62.4 = 0.170 \text{ cu. ft.} \\
 \text{Total} &= 1.582 \text{ cu. ft.}
 \end{aligned}$$

The quantities for 1 cu. yd. are as follows:

$$\begin{aligned}
 \text{Cem.} &= (27)(0.213) = 5.76 \text{ cu. ft.} = 1.44 \text{ bbl.} \\
 \text{F.A.} &= (27)(0.476) = 12.86 \text{ cu. ft.} \\
 \text{C.A.} &= (27)(0.723) = 19.54 \text{ cu. ft.} \\
 \text{Water} &= (27)(0.170) = 4.59 \text{ cu. ft.} = 34.34 \text{ gal.} \\
 \text{Total} &= 42.75 \text{ cu. ft.}
 \end{aligned}$$

and the proportions by bulk or loose volume are 1:2.23:3.39.

Note that the mixture selected corresponds to the intermediate mixture beneath Fig. 26, for which quantities and many other items are listed, as they also are for a rich mixture at the left and a lean one at the right.

Example 2. Extending the Design by Lyse's Method.—To determine the proportions by weight that should produce a concrete of about the same workability as that of the preceding example but with a strength of 5000 p.s.i., and also to determine the yield.

Solution.—Normally the solution of this problem would require another trial batch using the new water-cement ratio, which from Fig. 20 is found to be 0.44 by weight (c/w by absolute volume = 0.715). Since the materials are the same, as to both kind and grading and no change is specified for the workability, this problem can be solved by application of the Lyse approximations without the necessity of another trial batch. This adjustment is made as follows:

$$\begin{aligned}
 \frac{c}{w} \text{ (absolute volume)} \\
 &= 0.715 \text{ from Fig. 20 as noted above}
 \end{aligned}$$

But w remains unchanged at 0.170 and

$$c = (0.715)(0.170) = 0.122$$

Since

$$w + b \text{ remain unchanged at } 0.170 + 0.430 = 0.60$$

$$c + a \text{ remain unchanged at } 1.000 - 0.60 = 0.40$$

and

$$a = 0.400 - 0.122 = 0.278$$

The quantities for a unit volume of the 5000 p.s.i. mixture are (disregarding air voids as usual) as follows:

$$\begin{aligned}
 c &= 0.122 \text{ by abs. vol.} \\
 a &= 0.278 \text{ by abs. vol.} \\
 b &= 0.430 \text{ by abs. vol.} \\
 w &= 0.170 \text{ by abs. vol.}
 \end{aligned}$$

$$\text{Total} = 1.000 \text{ by abs. vol.}$$

Weights in 1 cu. ft. are as follows:

$$\begin{aligned}
 \text{Cem.} &= (0.122)(196.6) = 24.00 \text{ lb.} \\
 \text{F.A.} &= (0.278)(165.4) = 46.00 \text{ lb.} \\
 \text{C.A.} &= (0.430)(165.4) = 71.12 \text{ lb.} \\
 \text{Water} &= (0.170)(62.4) = 10.61 \text{ lb.} \\
 \text{Total} &= 151.73 \text{ lb.}
 \end{aligned}$$

Proportions by weight are

$$1:1.92:2.97 \text{ and the computed yield is } \frac{27}{3.91} = 6.91$$

These results may be readily expressed in whatever units are desired in accordance with the illustrations of Example 1.

80. Corrections for Absorption, Free Water in the Aggregates, and Bulking.

Example 3. Correction for Absorption of Mixing Water by the Aggregates.—To determine the amount of water that must be added to the mixing water to compensate for absorption by the fine and coarse aggregates. The absorption is shown on Line 13 of Table VI to be 1 per cent each for the fine and coarse aggregates.¹¹

Solution:

$$\begin{aligned}
 \text{Water extracted by F.A.} &= 13.31 \text{ lb. (1-cu. yd. batch)} \\
 \text{Water extracted by C.A.} &= 19.20 \text{ lb. (1-cu. yd. batch)} \\
 \text{Total} &= 32.51 \text{ lb. (1-cu. yd. batch)}
 \end{aligned}$$

The mixing water should be increased to $286.4 + 32.5 = 318.9$ lb. or to 38.3 gal. per cu. yd. to allow for absorption by the dry aggregate. If the correction is not made, the decrease of about 11.4 per cent in the amount of available mixing water

¹¹ The absorption allowance is for that which may be expected to take place during the first 15 to 30 minutes of immersion, since absorption after placement has no adverse effect on workability. Moisture supplied for hydration replaces any moisture loss subsequent to placement. For most aggregates a high percentage of the ultimate absorption is attained during the first few moments of immersion.

will probably make a substantial change in the workability. The correction to the mixing water must be applied for either weight or volume batching. Lines 43 to 49 of Fig. 26 summarize the data and calculations on absorption.

As mentioned previously, absorption by the aggregate is not a common field condition since aggregates on the job are rarely dry enough to extract water from the mixture. In the laboratory the aggregates in the bins usually are dry, but it is much better to bring the aggregate to the "saturated surface-dry" condition, prior to use, than to make an absorption correction in the amount of mixing water used.

Example 4. Correction for Free Water in the Aggregates (Batching by Weight).—To correct the quantities of mixing water and aggregates for free moisture contained in the aggregates. The corrections will be on the basis of the quantities required for a 1-cu. yd. batch for free-moisture contents of 4 and 1 per cent in fine and coarse aggregates, respectively (Table VI, Line 14). Batch measurements are by weight.

Solution.—The aggregate and free water are weighed and recorded as aggregate. If no correction is made, the batch will contain too much water and too little aggregate. The weights of moist aggregates required for a 1-cu. yd. batch, from Fig. 26, Lines 24 and 25, are as follows:

$$\text{F.A.} = (1.04)(1330.8) = 1384.0$$

of which 1330.8 lb. are F.A. and 53.2 lb. are water

$$\text{C.A.} = (1.01)(1920.3) = 1939.5$$

of which 1920.3 lb. are C.A. and 19.2 lb. are water

$$\begin{aligned} \text{Total water to be deducted} \\ \text{from mixing water} &= 72.4 \text{ lb.} \end{aligned}$$

Thus mixing water (Line 26) becomes

$$286.4 - 72.4 = 214.0 \text{ lb.}$$

Weights for both the saturated surface-dry aggregates and for the moist aggregates are listed below.

Original Design	Corrections	Modified to Correct for Free Moisture
Cem. 541.4	0.0	= 541.4
F.A. 1330.8	+ 53.2	= 1384.0
C.A. 1920.3	+ 19.2	= 1939.5
Water 286.4	- 72.4	= 214.0
Total 4078.9	0.0	4078.9

If the original design weights were used without correcting for the excess water, the actual quantities would be as follows:

Cem.	541.4	= 541.4
F.A.	$\frac{1330.8}{1.04}$	= 1279.6 (water 51.2)
C.A.	$\frac{1920.3}{1.01}$	= 1901.3 (water 19.0)
Water	286.4 + 51.2 + 19.0	= 356.6
Total		= 4078.9 70.2

If the weights are divided by the weight of the cement, the proportions are found to be as follows:

Initial design	1:2.46:3.55	$\frac{w}{c_{wt}} = 0.529$
Corrected design	1:2.55:3.58	$\frac{w}{c_{wt}} = 0.396$
Actual, if uncorrected	1:2.37:3.52	$\frac{w}{c_{wt}} = 0.659$

There is no serious discrepancy in the amounts of aggregates in this case, if no correction is applied.¹² However, the water-cement ratio is raised from 0.53 to 0.66, about 25 per cent, by the free water carried into the mixture. This increase adds greatly to the fluidity of the mixture and, more important, lowers the probable strength from about 4000 p.s.i. to about 2900 p.s.i. (see Fig. 20), a reduction of 1100 p.s.i., or nearly 30 per cent. The importance of free moisture in the aggregates increases for leaner mixtures.

Results for this example are tabulated in the middle column of Lines 50–61 of Fig. 26.

Example 5. Correction for Bulking of the Fine Aggregate (Batching by Loose Volume).—To correct the quantity of fine aggregate, required for a 1-cu. yd. batch, for a bulking of 20 per cent on the basis of the bulked volume (Table VI, Line 15).

Solution.—Assume that a one-unit measure of the fine aggregate, when either dried out or inundated, has been found to shrink 20 per cent, filling only 80 per cent of the measure. Thus the volumetric deficiency is 20 per cent of the bulked volume or 25 per cent of the unbulked volume of Fig. 26, Line 37.

$$\text{Amount of bulking} = (0.25)(12.86) = 3.2 \text{ cu. ft.}$$

$$\text{Required amount of bulked F.A.} = \frac{12.86}{0.80} = 16.1$$

¹² This is general; for batching by weight, which bulking does not affect, the correction for the free moisture is usually the only correction required.

cu. ft., and the quantities of the bulked material required will be as follows:

5.8:16.1:19.5 cu. ft. (Fig. 26, Lines 36-38)

with proportions as corrected 1:2.80:3.39 instead of 1:2.23:3.39 as designed.

If uncorrected the actual quantities would be 5.8:9.7:19.5 with proportions of 1:1.68:3.39, obviously an "undersanded" mixture. The effect of bulking (uncorrected) is always to make a mixture harsh (from lack of fine aggregate) and overwet, both from the lack of fine aggregate and from the moisture that causes the bulking. The correction for the free moisture is as outlined in Example 4. In loose volumetric proportioning, neither the effect of free moisture nor of bulking can safely be ignored. Results are summarized on Lines 62-65 of Fig. 26.

81. Effect of Air Voids on Quantities.

Example 6.—To determine the air voids in the concrete from a comparison of the computed unit weights (assuming no air voids present) and the unit weight observed from a unit-weight determination made in manner similar to A.S.T.M. Designation C138-39 or C29-39.

Solution.—Computed unit weight (no air voids) is 151.1 lb. per cu. ft. (Fig. 26, Line 20). Observed unit weight is 145.3 lb. per cu. ft.¹³ (Fig. 26, Line 66). If the sample of concrete was representative and the specific gravities of the constituent materials used for computing the volume of 151.1 were correct, the decrease in the observed weight must be the result of spreading of particles due to air voids. Thus the space actually occupied by solids plus water, t , is

$$\frac{145.3}{151.1} = 0.962, \text{ and the air voids are } 1 - 0.962 \\ = 0.038 = v_a$$

Then each unit volume of concrete as mixed contains only 0.962 of the volume of each material assumed for the values tabulated on Lines 6 to 9 of Fig. 26.

Corrected absolute volume quantities are as follows:

¹³ The observed unit weights for all three of the mixtures of Fig. 26, Line 66, have been assumed low enough to indicate air voids somewhat above those normally found in well-proportioned mixtures in order to exaggerate slightly the effects on the quantities. The actual mixtures of Fig. 27, for which no air voids are apparent, represent the other extreme (see also Question 30¹⁴).

$$\begin{aligned} c &= (0.962)(0.102) = 0.098 \\ a &= (0.962)(0.298) = 0.287 \\ b &= (0.962)(0.430) = 0.413 \\ d &= a + b + c = 0.798 \quad v = 1 - d = 0.202 \\ w &= (0.962)(0.170) = 0.164 \quad v_a = v - w = 0.038 \\ t &= a + b + c + w = 0.962 \\ v_a &= v - w = 0.038 \\ a + b + c + w + v_a &= 1.000 \quad \text{or } t + v_a = 1.000 \\ &\quad \text{or } d + v = 1.000 \end{aligned}$$

The yield will be about 4 per cent greater than that predicted (Fig. 26, Line 22). Yield (observed) = $4.69 \div 0.962 = 4.87$, an increase of about 0.2 cu. ft. per bag of cement.

Since the mixture has been assumed to have been spread or expanded uniformly, the relative amounts of all constituent materials are unaltered and

$$\begin{aligned} \frac{a}{c} &= \frac{0.287}{0.098} = 2.92 \text{ as on Fig. 26, Line 12} \\ \frac{c}{w} &= \frac{0.098}{0.164} = 0.60 \text{ as on Fig. 26, Line 13} \\ \frac{b}{a} &= \frac{0.413}{0.287} = 1.44 \text{ as on Fig. 26, Line 14} \end{aligned}$$

The proportions by absolute or solid volume are unchanged, being 1:2.92:4.22 (Fig. 26, Line 11).

82. Voids-cement Ratio and Other Absolute Volume Relationships.—The voids-cement ratio (the Talbot-Richart criterion for strength) parallels and is consistently somewhat higher than the water-cement ratio when also expressed in absolute-volume units. This is because the voids v represent the sum of water plus air instead of being just water.

Example 7.—To Compute the Voids-cement Ratio and Other Ratios or Quantities.

Solutions:

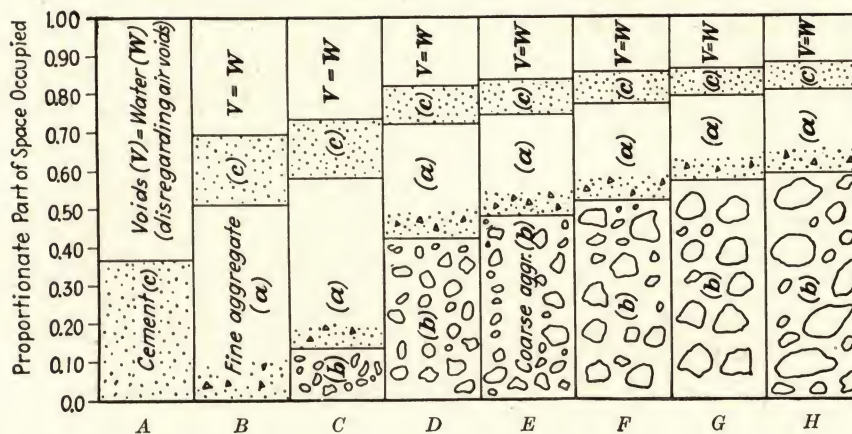
$$\frac{v}{c} = \frac{0.202}{0.098} = 2.06$$

$$\frac{w}{c} (\text{abs. vol.}) = \frac{0.164}{0.098} = 1.67$$

$$\text{Cement-space ratio, } \frac{c}{v + c} = \frac{0.098}{0.202 + 0.098} = 0.327$$

The ratio b/b_0 constitutes a useful criterion for judging the extent to which the ultimate in economy is approached as judged by the closeness with which the amount of coarse aggregate in the concrete approaches the amount of rodded coarse aggregate the form would hold with no mortar present. Thus for this mixture¹⁴ $b/b_0 = 0.413/0.617 = 0.671$.

¹⁴ The number 0.617 is from Col. (e). Line 8 of Table VI.



Properties and characteristics of mixtures of Figs. 27 and 28. (Boulder Dam materials.)*
 Paste constant; mortars constant for B, C, D, E, F, G, H; coarse aggregate graded alike to maximum size used.

1. Mixture	A	B	C	D	E	F	G (Boulder Dam Mix)	H (Boulder Dam Mix)
2. Max. size C. A. (in.)	Paste only	Mortar only	$\frac{3}{8}$	$\frac{3}{4}$	$1\frac{1}{2}$	3	6	9
3. Adaptations	.....	Rarely used		Usual construction		Dams and other mass construction		
4. Mortar prop. by wt.	neat	1:2.45	1:2.45	1:2.45	1:2.45	1:2.45	1:2.45	1:2.45
5. C.A. parts by wt.	none	none	0.75	3.60	4.35	5.30	6.47	7.05
6. w/c by wt.	0.54 = 6.2 gal./bag	= 0.82 loose vol.	= 1.70 abs. vol.	(Estimated strength 3900 p.s.i.)				
7. Slump approx. (in.)	fluid	too thin	9	8	5	Aggregate too large for slump	156	156
8. Unit wt. (weighed) lb. per cu. ft.	not determined		143	147	151	153	156	156
9. Unit wt. (computed) lb. per cu. ft.	112	140	144	152	153	156	157	157
10. Cem. by abs. vol. (c)	0.370	0.177	0.154	0.102	0.093	0.085	0.076	0.072
11. F.A. " " (a)	.....	0.520	0.448	0.297	0.272	0.247	0.222	0.210
12. C.A. " " (b)	.....	.....	0.135	0.428	0.477	0.524	0.572	0.595
13. Water " " (w)	0.630	0.303	0.263	0.173	0.158	0.144	0.130	0.123
14. Total " " (t)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
15. Solidity ratio = $a + b + c = d$	0.370	0.697	0.737	0.827	0.842	0.856	0.870	0.877
16. a/c by abs. vol.	.....	2.92	2.92	2.92	2.92	2.92	2.92	2.92
17. b/a " " "	.....	.....	0.30	1.43	1.75	2.12	2.57	2.84
18. c/w " " "	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.59
19. b/ba " " "	.....	.....	.....	0.685	0.730	0.760	0.805	0.826
20. Yield (cu. ft./bag cem.)	1.29	2.68	3.10	4.70	5.16	5.61	6.30	6.65
21. Cem. (bbl./cu. yd.)	5.24	2.52	2.15	1.44	1.31	1.20	1.07	1.01
22. Water (gal./cu. yd.)	127	61.5	52.5	35.2	32.1	29.4	26.2	24.6
23. Str.-econ. index (str. est.) p.s.i.	186	360	452	675	744	810	910	965
24. Prop. by wt.	1:0:0	1:2.45:0	1:2.45:0.75	1:2.45:3.60	1:2.45:4.35	1:2.45:5.30	1:2.45:6.47	1:2.45:7.05
25. Prop. by abs. vol.	1:0:0	1:2.92:0	1:2.92:0.88	1:2.92:4.20	1:2.92:5.10	1:2.92:6.20	1:2.92:7.55	1:2.92:8.22
26. Prop. by loose vol.	1:0:0	1:2.10:0	1:2.10:.....	1:2.10:3.27	1:2.10:3.73	1:2.10:4.30	1:2.10:5.10	1:2.10:5.47
27. Cem. wt. in 1 cu. yd. (lb.)	1970	940	820	540	490	450	400	380
28. F.A. " " " "	.....	2320	2000	1320	1210	1100	980	930
29. C.A. " " " "	.....	.....	630	1940	2160	2400	2620	2700
30. Water " " " "	1060	520	450	300	270	250	220	210
31. Concr. " " " "	3030	3780	3900	4100	4130	4200	4220	4220

Grading and properties of aggregates (Arizona natural sand and gravel).
 Fine aggregate identical. Coarse aggregate gradings all alike to maximum size used.

	none	0—No. 4	No. 4— $\frac{3}{8}$ in.	No. 4— $\frac{3}{4}$ in.	No. 4—1 $\frac{1}{2}$ in.	No. 4—3 in.	No. 4—6 in.	No. 4—9 in.
32. Size (F.A. or C.A.)	none	0—No. 4	No. 4— $\frac{3}{8}$ in.	No. 4— $\frac{3}{4}$ in.	No. 4—1 $\frac{1}{2}$ in.	No. 4—3 in.	No. 4—6 in.	No. 4—9 in.
33. Fineness mod. (F.A. or C.A.)	.....	2.72	6.00	6.59	7.23	7.83	8.35	8.60
34. Fineness mod. (mixed aggr.)	.....	2.72	3.50	5.05	5.60	6.20	6.80	7.10
35. Specific gravity	3.11	2.64	2.70	2.70	2.70	2.70	2.70	2.70
36. Unit wt. solid (F.A. or C.A.)	.....	164.7	168.5	168.5	168.5	168.5	168.5	168.5
37. Unit wt. bulk	.....	109.6	.....	103.8	109.6	115.8	119.5	121.0
38. Solid. ratio, dry rodded (F.A. or C.A.)	.....	0.666	.....	0.623	0.653	0.690	0.709	0.721
39. Voids	.....	0.334	.....	0.377	0.347	0.310	0.291	0.279

* Data for calculated quantities secured from *Proc. Am. Concr. Inst.*, Vol. 31, pp. 282 and 284 (Tables 1 and 4), 1935.

Note: These calculations are based on data reported in *Proc. Am. Concr. Inst.* in which quantities were reported to only two or three significant figures in accordance with usual practice. For purposes of calculation results in a number of cases have been extended one or two places further for reasons indicated in Art. 22.

FIG. 27.—Effect of maximum size of graded aggregate upon economy and other characteristics of concrete (mortar constant).

This value indicates that unless the sand-cement mortar is relatively harsh, the mixture is somewhat oversanded and should be plastic rather

and the water

$$w_m = \frac{w}{1-b} = \frac{0.164}{1-0.413} = 0.280$$

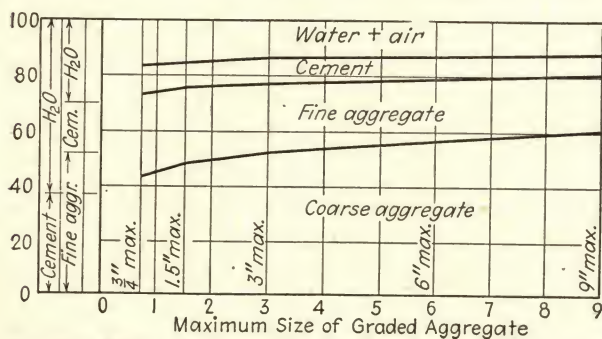


FIG. 28.—Effect of maximum size of aggregate on proportions.

than harsh. With a well-graded rather fat mortar, the value of b/b_0 can sometimes be made to approach 0.90 which marks about its upper limit. Values between 0.65 and 0.75 represent the usual upper limits. An attempt to get too much coarse aggregate into a mixture will result in harshness and honeycombing; wedging apart of fragments will be increased, and the mortar will be insufficient to fill all spaces between coarse aggregate particles. In like manner values of b and of the ratio b/a supply, for a given maximum size of aggregate, indications similar to those supplied by the b/b_0 ratio. For $1\frac{1}{2}$ -in. maximum size the usual limiting values for b are between 0.45 and 0.50 and for b/a between 1.50 and 2.00. For most concrete work it is best not to strain too hard in attempting to attain the economy that comes from using the maximum possible amount of coarse aggregate but to lean rather toward the side of the slightly oversanded mixtures. Limiting ratios are somewhat lower for angular particles than for rounded ones.

By the Talbot-Richart method of design the quality of the sand-cement mortar constitutes the criterion for predicting quality of concrete.

Voids in a unit volume of the mortar (v_m) are

$$v = v_m(1-b), \text{ or } v_m = \frac{v}{1-b} = \frac{0.202}{1-0.413} = 0.345$$

Note that the voids-cement and water-cement ratios for a mortar and its concrete are identical; the mortar simply contains relatively more voids, water, and cement than does the concrete. The mixtures of Fig. 27 illustrate this point. Thus the cement in a unit volume of the mortar,

$$c_m = \frac{c}{1-b} = \frac{0.098}{1-0.413} = 0.167$$

83. Discussion of Figs. 26, 27, and 28.—Figure 26 is a graphical representation embodying Lyse's assumptions and illustrating how a single trial-batch determination can be made to cover the entire useful range of concrete strengths for given aggregates and a specified workability.

The extensive tabulation beneath each of the three widely varying mixtures is intended to serve at least three useful functions.

a. It embodies practically all the items and terms which relate to the design and control of mixtures and should be useful as a ready source of reference for methods of calculating quantities and other items.

b. It affords an excellent basis for comparing the manner and degree to which different factors influence rich, medium, and lean mixtures.

c. The range of mixtures included is representative of those used for much of the current concrete work, and, within a wide scope, the diagram and tabulation show what may reasonably be expected from representative materials under normal conditions.

Figures 27 and 28 cover the full range of sizes of aggregates from cement paste to concrete with 9-in. cobbles, the largest aggregate ever passed through a concrete mixer. Whereas the mixtures of Fig. 26 are at constant grading and workability and at variable water-cement ratios, those of Figs. 27 and 28 are at constant water-cement ratio, have a constant mortar and a wide range of variation in the coarse aggregate as to both limiting size and amount. Figure 28 simply summarizes some of the evidence of Fig. 27 in a conventional manner.

Figures 26 and 27 (or 28) taken together supply two comprehensive and widely different cross sections of concrete mixtures. Comparative studies of the different mixtures represented may contribute much to an understanding of concrete even though within the scopes of these mixtures there is infinite room for further variations.

LABORATORY PROBLEMS

84. Recommended Series of Tests.—Problem 18 has as its primary objective the application of the trial-batch method to the design of a concrete mixture on the basis of a specified workability and a specified strength. Problem 19 constitutes a fol-

low-up partially to gain facility in the use of the method and partially to secure firsthand information regarding the effect of some major variable on the characteristics of the mixture and the properties of the concrete.

SERIES I.—TO INVESTIGATE THE VALIDITY OF THE LYSE METHOD FOR PRODUCING CONCRETE OF VARIABLE STRENGTH AT CONSTANT WORKABILITY

Line	Item	Batch No.						
		1	2	3	4*	5*	6*	7*
		(Base)			←Min. batch 0.2 cu. ft.→			
1	Design slump, in.	3	3	3			3	3
2	Design texture	←Plastic→					←Plastic→	
3	Design strength (by w/c Std. at 28 days, p.s.i.)	4900	3000	1700				
4	c/w abs. vol.	0.70	0.50	0.40		0		0
5	Cem. by abs. vol.	0.14	0.10	0.08	$a + c$	None	$a + c$	None
6	F.A. by abs. vol.	(a)			None	$a + c$	None	$a + c$
7	C.A. by abs. vol.	(b)	←Same as for base mix→					
8	Water (net) by abs. vol.	0.20	0.20	0.20	0.20	0.20		
9	Total abs. vol.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	a/c				0	∞	0	∞
11	b/a				∞		∞	
12	b/w	←Same as for base mix→						

* Batches 4, 5, 6, and 7 are purely manipulative. They are designed to study the limiting cases of substituting cement for all the fine aggregate and of substituting fine aggregate for all the cement. These batches are to be just large enough to secure measurements of slump (about 0.2 cu. ft.), and no specimens will be cast. Batches 6 and 7 are to be trial batches to determine the water requirement to produce the specified 3-in. slump (± 1 in.) for these limiting cases. (If the fine aggregate is somewhat harsh or low in fines, it will be impossible to secure satisfactory observations of slump from batches 5 and 7 because of the tendency for the sand and water to segregate rather than to join for forming a plastic mass.) Batch 4 should be mixed as a first approximation for Batch 6. Batch 4 as mixed will probably be found too dry for workability. Water can then be added to Batch 4 in measurable amounts until the condition for Batch 6 is attained. Batch 7 should then be mixed as a first approximation to Batch 5 since the desired 3-in. slump will probably be secured at a water content appreciably less than the 0.20 specified for Batch 5. After the correct slump for Batch 7 has been secured and the water requirement recorded, the remainder of the water needed to make Batch 5 may be added, and the slump (if not too wet for slump) should again be observed.

Accompanying tabulations designated as Series I, II, and III, respectively, represent three optional outlines for Probs. 18 and 19. The instructor will indicate the series that is to be carried through. These outlined series are independent of one another, and all three series can be used to advantage if time permits. The outlines are necessarily in skeleton form since the completion of the tabulation requires data that depend to some extent upon

the maximum size and characteristics of the aggregate and upon results which are to be secured from the trial-batch design of Prob. 18. The ever-important variables of curing and the free-moisture content at test are introduced as supplementary features of each series outlined.

The quantities shown in concomitant tabulations are the absolute or solid volumes required for a one-unit batch of concrete. A batch of 1 cu. ft. is sufficient for five 6-in. by 12-in. cylinders or for forty 3-in. by 6-in. cylinders. In order to secure a slump measurement, a batch must have a volume of at least 0.20 cu. ft.

85. Discussion of the Outlined Series.—In each of the three series Batch 2 is labeled "Base" and is to serve as the basis of comparison for the factors to be investigated in the series. The base batch is to be of the same proportions as the final batch to be designed in Prob. 18. Therefore, the values to be used for a and b are dependent on the results secured in that problem.

Batches 1 to 3 of Series I constitute a good test for the validity of Lyse's rule for making adjustments over a moderately wide range of mixtures. Batches 4, 5, 6, and 7 represent limiting cases, for studies of workability only, and it is not to be expected that these mixtures (No. 4 and 6 consisting only of cement, water, and coarse aggregate; and No. 5 and 7 without cement) will show similar workabilities for equal contents of water and coarse aggregates. They may be expected, however, to emphasize trends that may or may not be clearly apparent within the range covered by Mixtures 1 to 3. Follow the detailed procedure given in the note below the tabular outline for Series I.

Batch 1 of Series II is expected to illustrate a poorly proportioned mixture characteristic of attempts to use more than the valid limiting amount of coarse aggregate. Mixtures 2 to 4 are expected to supply excellent evidence indicating the essential validity of the water-cement-ratio (or the voids-cement-ratio) strength criterion over quite a range of mixtures. Within this range there may or may not be evidence that the coarse aggregate functions as something more than the inert filler which these two theories assume it does. Mixtures 5 and 6 represent extreme departures in grading and are expected to give strengths that differ substantially from those of the concrete mixtures. On the basis of other tests Mixture 5 (identical with the base mixture except that it contains no coarse aggregate) will be relatively thin and considerably

stronger than the concretes. On the other hand, for Batch 6, in which added fine aggregate has taken the place of the coarse aggregate, it is entirely possible that the "lean" mortar will be weaker than

exercised not to add too much fine aggregate at once, in order to avoid overrunning the desired consistency. With some aggregates it may be found desirable to alter the values which have been

SERIES II.—TO INVESTIGATE THE VALIDITY OF THE WATER-CEMENT RATIO OF ABRAMS (OR THE VOIDS-CEMENT RATIO OF TALBOT AND RICHART) AS A CRITERION FOR STRENGTH OF CONCRETE
Water-cement ratio Constant; Workability Altered by Varying Relative Amounts of Coarse Aggregate

Line	Item	Batch No.					
		1	2	3	4	5	6
			(Base)			Mortar	Mortar
1	<i>c/w</i> , abs., vol.	0.50	0.50	0.50	0.50	0.50	0.50
2	<i>w/c</i> , gal. per bag	7.15	7.15	7.15	7.15	7.15	7.15
3	Design strength (by <i>w/c</i>) Std. at 28 days, p.s.i.	3000	3000	3000	3000	3000	3000
4	<i>a/c</i>	Same as for base mix					Larger
5	<i>b/a</i>					0	0
6	Cem. by abs. vol.	(c)	0.10				
7	C.A. by abs. vol.			0.35	0.20	None	None
8	Water (net) by abs. vol.		0.20				
9	Total abs. vol.	(w)	1.00	1.00	1.00	1.00	1.00
10	Probable slump, in.		0 to 1	3	4 or 5	6 or 8	8 or 10
11	Probable texture		Harsh under-sanded	Plastic	Fat over-sanded	Wet and thin	Fluid

SERIES III.—TO INVESTIGATE EFFECTS OF SOME EXTREME GRADINGS OF AGGREGATE ON WORKABILITY AND STRENGTH OF CONCRETE
Proportions and Water-cement Ratios Constant

	Item	Batch No.					
		1	2	3	4	5	6
		Mortar	Base	Mortar			
1	Proportions by abs. vol.	Same as for base mix					
2	C.A.—size range	None	$\frac{1}{4}$ – $1\frac{1}{2}$ *	0–4†	$\frac{3}{8}$ – $\frac{1}{2}$	$\frac{3}{4}$ –1	$1\frac{1}{4}$ – $1\frac{1}{2}$
3	<i>c/w</i> , abs. vol.	0.50	0.50	0.50	0.50	0.50	0.50
4	<i>w/c</i> , gal. per bag	7.15	7.15	7.15	7.15	7.15	7.15
5	Design strength (by <i>w/c</i>) Std. at 28 days, p.s.i.	3000	3000	3000	3000	3000	3000
6	Cem. by abs. vol.	(c)	0.10				
7	C.A. by abs. vol.			To equal that for base mix if possible‡			
8	Water (net) by abs. vol.		0.20				
9	Total abs. vol.	(w)	1.00	1.00	1.00	1.00	1.00
10	<i>a/c</i>	Same for all					
11	<i>b/a</i>	Same for all if possible					
12	Expected slump, in.	High	3	0–0.5	0–1	1–2	3–4
13	Expected texture	Fluid	Plastic	Dry	Undersanded	Workable	Slightly wet

* To correspond to size range for base mixture in case some other grading is used.

† No coarse aggregate actually to be used. Extra sand to be added in same amount as coarse aggregate (or to the limit of workability) and, for purpose of comparison, is to be treated as coarse aggregate.

‡ It may not be possible to add full amount of sand, or $\frac{1}{4}$ to $\frac{1}{2}$ C.A., without stiffening to point of nonworkability.

the moderately "rich" concrete of Batch 2. The amount of fine aggregate required to produce for Batch 6 about the same workability as that of Batch 2 will be found by trial. Care needs to be

assigned for *b*. If, for example, the maximum size of the coarse aggregate being used is $\frac{3}{4}$ in. or 1 in., the indicated values of *b* will be too high. The data secured initially in designing Batch 2 will supply

the information needed to select a suitable range of values for the coarse aggregate contents of related mixtures.

In certain respects Series III covers comparisons resembling some of those of Series II. Note especially that Mixture 3 is really a mortar but is being made to cover the extreme case in which the coarse aggregate is replaced by fine aggregate. As has been indicated in the footnotes, it is unlikely that the full amount of coarse aggregate (or coarse aggregate substitute) that has been specified can be gotten into either Batch 3 or Batch 4 without a complete sacrifice of workability. For these two batches it is suggested that the coarse aggregate be added gradually to avoid overrunning the limit of workability. Series III should serve to illustrate the lack of economy and other objections to using poorly graded aggregates.

86. Supplementary Tests Relating to Concrete and Concrete Aggregates.—Where there is no separate course covering the general field of plain concrete and concrete materials, the scope of the work in concrete may well be amplified to include such supplementary problems as those covered by the A.S.T.M. Designations which follow. The instructor will find it necessary to supply little if any explanation, beyond that given in the standard itself.

Title	A.S.T.M. Designation
Flexural Strength of Concrete.....	C78-39
The Physical Testing of Portland Cement.....	C77-40
Specific Gravity and Absorption of Coarse Aggregate.....	C127-39
Specific Gravity and Absorption of Fine Aggregate.....	C128-39
Sieve Analysis of Fine and Coarse Aggregates.....	C136-39
Surface Moisture in Fine Aggregate.	C70-30
Unit Weight of Aggregate.....	C29-39

The current A.S.T.M. Standards include about 50 designations which relate to concrete materials, equipment, and tests.

NOTATION, DEFINITIONS, REFERENCES, AND QUESTIONS

87. Definitions, Notations, and Formulas.—Not all the following are encountered in routine work but most of them are illustrated in the tabulations beneath Figs. 26 and 27.

Cem. = abbreviation for portland cement.

F.A. = abbreviation for fine aggregate; usually natural sand or crushed stone which

passes the No. 4 standard sieve as detailed in A.S.T.M. Designation E11-39.

C.A. = abbreviation for coarse aggregate; usually natural gravel or crushed stone large enough to be retained on the No. 4 sieve (see F.A.).

c = absolute or solid volume of cement in a unit volume of freshly mixed concrete (see also w/c).

a = absolute or solid volume of fine aggregate in a unit volume of freshly mixed concrete.

b = absolute or solid volume of coarse aggregate in a unit volume of freshly mixed concrete.

d = solidity ratio of cement, aggregate, or freshly mixed concrete. (Called *density* by Talbot and Richart, but that term is avoided here because of its conflict with the prior well-established definition of density as used in the entire field of science and engineering.) For concrete $d = c + a + b$ = the absolute or solid volume of the solid constituents in a unit volume of freshly mixed concrete. It is also equal to $1 - v$ (see voids). In general d is the absolute volume of the solid particles present in a unit volume of the material (the ratio of the absolute volume of solid particles to the bulk or volume occupied by the mixture).

t = total absolute or solid volume of all the constituents in a mixture exclusive of air. $t = 1 - v_a$. Also $t = c + a + b + w$ or $d + w$. Note: This term supplements those defined and used by Talbot and Richart (p. 16 of Reference *g*, Art. 89).

v = voids in a unit volume of freshly mixed concrete. $v = 1 - (a + b + c) = 1 - d$; likewise $v = v_a + w$ (see voids). v is also used to designate the voids in a unit volume of cement or aggregate determined according to A.S.T.M. Designation C30-37.

w = the volume of the free water in a unit volume of freshly mixed concrete (see also w/c and voids). $w = t - d$.

v_a = air voids in a unit volume of freshly mixed concrete (see also voids). $v_a = 1 - t = 1 - d - w$; also $v_a = v - w$.

v_m = voids in the mortar. The total voids in a workable concrete are the voids in its mortar, providing the mortar is sufficient to occupy all spaces between particles of the coarse aggregate. (This is, in fact, one of the criteria for a workable concrete.)

w_m = the water in the mortar, similar to the voids in the mortar as just explained.

b_0 = solidity ratio of the coarse aggregate in the compact or dry rodded condition = $1 - v$.

a/c = ratio of fine aggregate to cement by absolute or solid volume.

b/a = ratio of coarse aggregate in a batch to the fine aggregate by absolute or solid volume.

b/b_0 = ratio of absolute or solid volume of coarse aggregate in a unit volume of freshly mixed concrete to the absolute or solid volume of the compact coarse aggregate required to fill a unit measure. If the mortar could surround the particles of aggregate as a liquid without any wedging or prying apart of particles, the limiting value of the ratio would be unity. Actual limiting values for practical conditions usually lie between 0.65 and 0.75. Rounded or well-graded particles permit higher values than do angular or poorly graded particles. Vigorous compaction of the concrete, as by vibration, increases the limiting value above that attainable with most other methods of placement.

w/c = water-cement ratio (the Abrams criterion for strength). The ratio of the net mixing water to the cement in any portland-cement mixture. The ratio is not limited to terms of absolute or solid volumes as would be indicated by the definitions previously given for w and c . Actually the ratio is widely expressed by weight both in the laboratory and in the field. It is also expressed as gallons of water per bag of cement and in terms of loose or bulk volumes. It is always desirable, and usually essential for clarity, that an indication be given as to which w/c is meant, as w/c by weight, w/c in gal. per bag, etc.

c/w = cement-water ratio. Like its reciprocal, w/c , c/w may be expressed in a variety of units. The only ones in current use are weight and absolute or solid volume, but units need always to be indicated in order to make clear which of these applies.

v/c = voids-cement ratio, the Talbot-Richart criterion for strength. Always expressed in absolute-volume units. If there were no air voids in freshly mixed concrete, v/c would be identical with w/c (when the latter is expressed in absolute-volume units). For usual plastic mixtures v/c parallels and slightly exceeds w/c . For unworkable mixtures the difference may be considerable.

$\frac{c}{c+v}$ = cement-space ratio, a supplementary Talbot-Richart criterion for strength. It is expressed in absolute-volume units and more or less parallels the cement-water ratio c/w within the range of plastic mixtures.

The following summary of statements and relationships follows directly from some of the definitions given and is useful for computing certain absolute-volume quantities (page 16 of Reference *g*, Art. 89).

- (1) $a + b + c = d = 1 - v$
- (2) $\frac{c + a}{1 - v_m}$ = space occupied by the mortar in freshly mixed concrete
- (3) $\frac{c + a}{1 - v_m} + b = 1$ = composition of a unit volume of concrete
- (4) $v = v_m(1 - b)$ or $b = 1 - \frac{v}{v_m}$
or $v_m = \frac{v}{(1 - b)}$

from (1) and (3)

- (5) $t = \frac{\text{observed unit wt. (A.S.T.M. C29-39)}}{\text{computed unit wt. assuming no air voids}}$
= $\frac{\text{observed unit wt.}}{\text{sum of weights of } c, a, b, \text{ and } w}$
- (6) $v_a = 1 - t$

If c , a , b , and w are absolute volumes assumed or computed on the basis of no air voids, the corrected values are tc , ta , tb , and tw , respectively.

88. Supplementary Definitions and Illustrations.

ABSOLUTE OR SOLID VOLUME: as applied to cement or aggregates, the term means the volume that the solid particles would displace in a liquid.

Illustration.—One cubic foot of cement, absolute volume, weighs $(3.15)(62.4) = 196.6$ lb.

BULK VOLUME: total volume required to accommodate a material, being equal to the absolute volume plus the voids.

Illustration.—One cubic foot of cement by compact bulk volume weighs 94 lb.

Solidity ratio d of 1 cu. ft. cem. by compact bulk

$$\text{volume} = \frac{94}{196.6} = 0.478$$

Voids v in 1 cu. ft. cem. by compact bulk volume
 $= 1 - d = 0.522$

FREE WATER: water that lies without the boundaries of solid particles of cement or aggregate. Includes adsorbed but not absorbed water.

NET MIXING WATER: all the nonabsorbed water in a mixture; water available for lubricating the mixture. Much of the net mixing water will normally be available for subsequent hydration of the cement, as that phase gets under way.

ABSORBED WATER: water that lies within the boundaries of aggregate particles and is so held by capillarity as to be unavailable for lubrication of the mixture or for hydration of the cement.

CEMENT FACTOR: relative amount of cement in a concrete mixture. May be expressed as bags or barrels of cement per cubic yard of concrete in place.

YIELD: volume of compacted concrete secured from a one-bag batch. The greater the yield, the lower will be the cement factor.

STRENGTH-ECONOMY INDEX: The 28-day standard compressive strength of the concrete divided by the number of bags of cement per cubic yard of the concrete in place.

89. References.

- a. Chapter on concrete in textbooks on properties of engineering materials.
- b. A.S.T.M. Designation C39-39.
- c. Design and Control of Concrete Mixtures, *Bull.* T-12, Portland Cement Association, Chicago, Ill.¹⁵
- d. Dunagan, W. M. "Manual of Control Tests for Portland Cement Concrete," Ames, Iowa, 1939.

¹⁵ This publication contains reprints of many of the A.S.T.M. Standards relating to concrete and much other useful material.

Also, A Proposed System for the Analysis and Field Control of Fresh Concrete, *Iowa Eng. Expt. Sta. Bull.* 113, 1933.

- e. "Concrete Manual," 2d ed., U. S. Bureau of Reclamation. Published in Denver, Colo., 1940.
- f. Report of Third Joint Committee on Specifications for Concrete and Reinforced Concrete, 1940.
- g. Talbot, A. N., and F. E. Richart. *Univ. Illinois Eng. Expt. Sta. Bull.* 137, 1923.
- h. Bauer, E. E. "Plain Concrete," 2d ed., McGraw-Hill Book Company, Inc., New York, 1936.
- i. Troxell, George E., and Harmer E. Davis. "An Introduction to the Making and Testing of Plain Concrete," a photolith, Stanford University Press, Stanford University, Calif., 1938.
- j. McMillan, F. R. "Basic Principles of Concrete Making," McGraw-Hill Book Company, Inc., New York, 1929.
- k. Report on Significance of Tests of Concrete and Concrete Aggregates, published by A.S.T.M., Philadelphia, Pa., 1935. 2d ed., scheduled for 1941.
- l. Lyse, Inge. Simplifying Design and Control of Concrete Mixes, *Eng. News-Record*, Vol. 108, No. 7, pp. 248-249, Feb. 18, 1932.
- m. Dunagan, W. M. The Application of Some of the Newer Concepts to the Design of Concrete Mixes, *J. Am. Concrete Inst.*, pp. 649-684, June, 1940; also *Proc.*, Vol. 36, pp. 649-684, 1940.
- n. Kellermann, W. F. Designing Concrete Mixtures for Pavements, *Proc. A.S.T.M.*, Vol. 40, pp. 1055-1072, 1940.
- o. General sources for past and current literature on concrete.
 - (1) *American Concrete Institute. Journal and Proceedings.* The A.C.I. is probably the most important single source of published concrete material, being the one important organization dedicated noncommercially to that field alone. Since 1930 the A.C.I. has maintained a department of current reviews or abstracts which covers rather well the current literature of concrete. Recently, August 1941, the Institute has issued the "A.C.I. Manual of Concrete Inspection," a booklet of 137 pages. For detailed information regarding conditions of membership, services offered and literature available, address Harvey Whipple, Secretary, 7400 Second Boulevard, Detroit, Mich.
 - (2) Portland Cement Association, 33 West Grand Avenue, Chicago, Ill. A commercial Service Bureau supported by cement manufacturers. An excellent source of information, especially that relating to current problems and practice.
 - (3) *Concrete.* A monthly publication available in most technical libraries.
 - (4) *Concrete and Constructional Engineering.* One of the most important of the European publications. Published monthly in London and generally available in technical libraries.
 - (5) Among the publications not devoted solely to concrete and which are generally available in libraries are the following:

American Society for Testing Materials—Annual Proceedings; also the *A.S.T.M. Bulletin* published from four to eight times a year.

American Society of Civil Engineers—Proceedings.

Transactions (bound material which has appeared in the *Proceedings*).

Civil Engineering (monthly).

Public Roads—A monthly journal published by the Public Roads Administration.

Highway Research Board of the National Research Council—*Annual Proceedings*.

Engineering News-Record—Leading weekly publication in the field of civil engineering.

Technologic and Scientific papers published by the National Bureau of Standards and available by purchase from the Superintendent of Documents, Washington, D. C.

Engineering Experiment Station Bulletins, especially from some of the more important stations, such as: University of Illinois, Iowa State College, The Ohio State University, and Purdue University. The universities or colleges of a number of other states, including Maine, Wisconsin, Michigan, Kansas, Washington, and Oregon occasionally publish material in the field of concrete. Bulletins can be secured from some of these institutions without charge upon request.

Boulder Canyon Project, Final Reports. U. S. Bureau of Reclamation, Denver, Colorado, and Washington, D. C. A series of bulletins in process of publication (1938—) several of which deal with such phases as the concrete manufacture, handling, and control and the extensive concrete research in connection with Boulder Dam.

SUPPLEMENTARY QUESTIONS

283. How does concrete differ from timber, steel, stone, terra cotta and brick as regards the condition in which it is delivered to the job?

284. a. As one of the primary materials used in building construction, concrete takes its place beside steel and timber. From the standpoint of assuring acceptable material how does concrete differ from these?

b. Is the difference one of kind or of degree?

285. What constitutes the design of a concrete mixture?

286. a. What is meant by "control" as applied to concrete construction?

b. Distinguish between "quality-control" and "job-control" specimens.

c. What are the inherent advantages and disadvantages of quality control?

d. What are the inherent advantages and disadvantages of job control?

e. If but one type of control is to be used, which of these should generally be adopted as being the primary method of control?

287. Discuss briefly the relative importance of the properties listed, indicating any special situations under which a given property may be particularly important.

a. Strength.

b. Economy.

c. Consistency.

d. Durability.

e. Volume change.

f. Heat of hydration.

g. Plastic flow.

h. Appearance.

288. Does durable concrete always insure a durable structure?

289. a. State "the water-cement-ratio law" of Abrams.

b. According to this "law" what is the sole function of aggregate in concrete?

c. There are quantities of published data which show the essential correctness of the water-cement-ratio generalization within its usual range of application. Are there valid published data which show its limitations; which indicate beyond question that there can be and are important variations "within the law"?

d. Does the fact that it is probably far-fetched to call this relationship a law decrease its usefulness or detract from the credit that is due the man who through his researches first recognized the usefulness of the relationship and gave expression to it?

290. a. What names are associated with the voids-cement-ratio technique for the design of concrete mixtures?

b. Is the voids-cement ratio as a criterion for strength similar to or greatly different from the water-cement ratio?

c. Are there important variations within "the voids-cement-ratio law"?

d. What important concept did the voids-cement-ratio technique introduce in the design of mixtures?

291. a. (1) Explain how a plastic mixture can have more than one water-cement (or

voids-cement) ratio during the period prior to hardening.

- (2) Which of the several is the ratio that should correspond to the strength developed?
- b. Are special efforts ever made to extract water from concrete during or immediately following placement? Why?
- c. Is the free-water content of hardened concrete virtually equal to the voids, as is the case for plastic concrete? Explain.
- d. Are the voids in hardened concrete the same in volume as those in the mixture as it stiffens?
- e. Sometimes alleged determinations of the voids in hardened concrete have been made as follows:
 - (1) By noting the weight of water that an air-dry (or oven-dried) specimen will absorb on the assumption that the volume of the voids equals the volume of water absorbed.
 - (2) By the reverse process of first soaking the specimen to virtually constant weight and noting the amount of water that can be driven off by oven-drying to constant weight.

Explain why neither of these methods gives a correct indication of the voids in the concrete.

292. a. The curing process is not, as the layman often believes, one of drying out. What does happen when cement hydrates?
- b. What conditions are essential to the hydration of portland cement, and what happens when these conditions are not met or are interrupted?
- c. What happens when concrete freezes
 - (1) Immediately after placement?
 - (2) After a few hours?
 - (3) After several days of favorable curing?
 Discuss remedies.
- d. Is the curing of normal portland-cement concrete complete at the end of 28 days? Explain.
- e. For which is the water requirement greater for an ordinary concrete mixture
 - (1) To lubricate the mixture and to supply the mobility essential for placement?
 - (2) To meet hydration needs? Explain what would happen to concrete that

was sealed against either loss or gain of moisture immediately after placement.

- f. Is concrete unique in its characteristic of gaining in strength upon drying out and undergoing a corresponding reduction in strength after a few hours of resoaking?
- g. Does oven-drying increase the strength of concrete?
- h. How does the amount of normal air-drying shrinkage of typical pavement concrete compare with the shrinkage of clay under similar conditions?
- i. Discuss the relative importance of thorough early moist curing for the following concrete constructions:
 - (1) The concrete of a dam.
 - (2) A concrete pavement slab.
 - (3) A reinforced-concrete building.
293. a. How does bulking of the fine aggregate affect measurement of quantities
 - (1) If batches are weighed?
 - (2) If batches are measured by loose volume?
- b. How do errors in specific gravity affect the measurement of quantities?
- c. Are the number of significant places to which amounts of fine aggregate, coarse aggregate, and cement are carried in the illustrative examples and tabulated results indicative of the number of figures that should be retained as a matter of job practice?
294. a. Why is free water in the aggregate objectionable?
- b. For which of the aggregates (coarse or fine) is free water the more disturbing? Explain.
- c. How are free-water difficulties best handled
 - (1) In the laboratory?
 - (2) On the job?
295. a. What is bulking?
- b. Under what conditions may it be an objectionable factor in the proportioning of concrete materials?
- c. How may its objectionable features be avoided or overcome?
296. a. Why is absorption by the aggregate objectionable?
- b. For which of the aggregates (fine or coarse) may absorption be the more objectionable? Why?

- c. How may the difficulties from absorption be overcome
 - (1) In the laboratory?
 - (2) On the job?
 - d. With respect to extraction of mixing water from the batch, the absorption after about 15 min. soaking is as good as saturation. Explain why.
- 297.** a. Why do the specific gravities of the cement and aggregates need to be known?
- b. The specific gravity of saturated or partially saturated aggregate is somewhat greater than that of aggregate which is dry. Which of these several specific gravities should be used as the basis for determining the batch weights? Explain why.
- 298.** Of what significance is the term "probable strength in pounds per square inch per bag of cement per cubic yard of concrete"?
- 299.** The first A.S.T.M. Standard for portland cement was C9, adopted in 1904 and revised in 1908, 1909, 1916, 1920, 1926, 1930, 1937, and 1938. While various high-early-strength portland cements have been on the American market since 1925 or earlier, there was no separate A.S.T.M. Standard for high-early-strength portland cement until the adoption of C74 in 1936. Low-heat and modified portland cements were developed in connection with Boulder (Hoover) and other large dams for which special government specifications were written, but none of these cements have heretofore been standardized by the A.S.T.M. A.S.T.M. Designation C150-41 on portland cement was evolved not only to replace C9 and C74 but to include some of the other portland cements for the standardization of which need had developed.
- a. What two important changes in point of view are incorporated in C150? Explain.
 - b. The A.S.T.M. Standards include specifications for Natural Cement (C10-37), Keene's Cement (C61-40), and Masonry Cement (C91-40). Why are these not included among the cements of A.S.T.M. Designation C150?
- c. When the term *portland cement* is used without qualification which of the several cements of *a* is meant?
 - d. (1) What is the criterion on the basis of which any required or proposed chemical test of portland cement should be judged?
 - (2) What is the corresponding criterion for any physical test?
 - (3) What are some of the recent changes in the type of physical test required?
 - e. During a period of rapid development or change in any engineering material (of which portland cement is a good example), use will outstrip formal standardization. During such a period of flux, how best may one avoid becoming unduly confused in attempting to keep himself correctly informed?
- 300.** The primary function of aggregate in concrete is that of inert filler, to dilute the cement. Are all natural rocks and sands, if properly graded and reasonably strong and sound, suitable for aggregate? Explain.
- 301.** One of the most basic and longstanding concepts of concrete has been that the strongest, best, and most durable concretes are those in which the void contents are the lowest or for which the solidity ratio is the highest. Within the past year or two it has been discovered that the addition of certain materials, such as some tallows and resins in small amounts, may increase the air voids from a maximum of perhaps 4 per cent for a lean but workable mixture to as much as 8 or 10 per cent with no decrease in workability. The strength of such concrete is generally somewhat reduced, but its resistance to freezing and thawing seems to be increased greatly.
- a. Does such an indication, if correct, mean that our previous conceptions regarding the merits of low-void concrete are erroneous and must be discarded? Explain if possible.
 - b. Under what conditions might it be proper to sacrifice some strength for added durability?

PROBLEM 18

Design of Concrete Mixtures

A. Object.—To study the characteristics of concrete mixtures and to determine the proportions of cement, water, fine aggregate, and coarse aggregate

to produce concretes of specified workabilities and strengths.

B. Materials.—Cement and saturated surface-dry aggregate as assigned by the instructor. Ascertain the predetermined specific gravity of each material from the instructor.

C. Equipment.—Scales, batch pan, trowel, slump cone, flow table (if available), rule, tamping rod, standard measure¹⁶ pails, and standard cylindrical molds. If the maximum size of coarse aggregate does not exceed 1 in., 3-in. by 6-in. molds may properly be used.

D. References.—Design and Control of Concrete Mixtures *Portland Cement Assoc. Bull.* T-12. A.S.T.M. Designations C39-39, Method of Test for Compressive Strength; C143-39, Method of Test for Slump; C124-39, Method of Test for Flow by Flow Table; C138-39, Method of Test for Yield of Concrete.

E. Determinations to Be Made.

1. Observations of texture, slump, flow, and unit weight of concrete of variable consistency at constant cement-water ratio.

2. The design by the trial-batch method of a plastic concrete mixture of 3-in. slump (± 1 in.) with a cement-water ratio corresponding to a standard-cured 28-day strength of 3000 p.s.i. (or other designated characteristics).

3. The design, by adjustment of the proportions of the base batch of Item 2 in accordance with the Lyse method, of batches having the same workabilities as the preceding one but with predicted strengths 25 per cent higher and 25 per cent lower, respectively.

4. The yields, proportions, and the other significant characteristics tabulated on data sheets No. 1 and No. 2.

5. The actual standard-cured 28-day strengths of four batches—the final mixture of Item 2 and the three batches of Item 3.

F. Procedure.

1. *Preparation for the Test.*—Weigh out 6 lb. of cement. For the strength specified and an assumed maximum size of coarse aggregate of $\frac{3}{4}$ in. or over, this should be sufficient to produce a batch of about 0.25 cu. ft. of concrete. (The volume of a standard slump cone or a 6-in. by 12-in. cylinder is about 0.20 cu. ft.) From the specified strength and Fig. 20 determine the required value of the cement-water ratio, and have the instructor check the calculation

¹⁶ Regardless of the maximum size of aggregate in the batch the observations for unit weight and yield will have to be taken with the standard 0.10 cu. ft. measure unless the volume of the batch exceeds 0.50 cu. ft.

for the amount of water that will be needed. Record the total weight of a pail or other vessel which contains at least 12 lb. of fine aggregate and of another that contains at least 24 lb. of coarse aggregate. Amounts of aggregate used from these pails can be easily determined as differences between over-all weights before and after the design operations.

2. Preliminary Tests.

a. Place about 6 lb. each of the fine and coarse aggregates in the dry mixing pan, spread them evenly, and add the weighed 6 lb. of cement over the surface. Mix the dry materials thoroughly to uniform color.

b. Form a large crater, and add the mixing water to the batch by pouring it gently into the crater. Mix the water with the materials by carefully working in the material from the inner side of the crater until the mixture has stiffened sufficiently to avoid possibility of splashing. The batch may then be mixed to uniformity.

c. Add fine and coarse aggregate to the batch in small increments. Preserve such a balance between coarse and fine aggregates that the mixture is at all stages plastic rather than either harsh or unduly fat. When the mixture appears to have become concrete of rather fluid consistency (an estimated slump of 6 or 7 in.), make slump, flow, and unit weight determinations, and record the over-all weights of the aggregate containers. Record the textural appearance as harsh (under-sanded), plastic (workable), or fat (over-sanded). Resume the gradual addition of fine and coarse aggregates until an estimated slump of about 3 in. is attained, and repeat the observations. Repeat again for a stiff consistency having an estimated slump of 0 to 1 in. With due regard for the stiffness and poor workability of low-slump mixtures, cast a cylinder or cylinders from the final mixture.

3. Final Tests.

a. Repeat the preparations as before but with the following abbreviations. If the plastic mixture of Item 2 c proved to have the slump and texture desired, the proportions may simply be duplicated to produce the base mixture for these tests. Generally some modification will be desired

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 Date 1-29-41 Wed. Observer (b) Doe, John
 Section 2 Computer (c) Johnson, W. S.
 Squad No. 3 Kit No. 5 Helper (h) _____

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DESIGN OF CONCRETE MIXTURES (Trial Batch Method)

Data sheet No. 1 Materials and Record of Laboratory Data.

MATERIALS															
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
1	Brand or source									Cem. Lehigh		F.A. Des. M. Riv.		C.A. Des. M. Riv.	
2	Kind									Type I		Sand (wash.)		Gravel	
3	Size											0-4		No. 4 - 1 1/2	
4	Fineness Modulus											2.70		7.10	
5	Bulk Spec. Gravity (A.S.T.M. C127 and C128)									3.15		2.65		2.65	
6	Solid unit wt. (lb. per cu. ft.)									196.6		165.4		165.4	
7	Compact unit wt. " " " "									94.0		108.4		102.0	
8	Solidity ratio (d)									0.478		0.657		0.617	
9	Voids in compact material (v)									0.522		0.343		0.383	
10	Condition as used											← Saturated Surface		Dry →	
11															
12															
13	Batch no.									1		2		3	4
14	Specified strengths									3000		3000		3750	2250
15	w/c by wt.									0.64		0.64		0.56	0.72
16	Specified slump (in.)									6-7	2-4	0-1	2-4	2-4	2-4
17	Cem. wt. in lb.									6.00		6.00			
18	Water " " "									3.84		3.84			
19	F.A. + pail (initial) (lb.)									20.00					
20	" " " (final) "														
21	" net wt. "														
22	C.A. + pail (initial) "									30.00					
23	" " " (final) "														
24	" net wt. "														
25	Time water added to batch														
26	" slump observed														
27	Slump (in.)														
28	Flow (%)														
29	Texture (fat, plastic, or harsh)														
30	Wt. filled std. measure														
31	" empty " "														
32	" concrete in " "														
33	Time spec. (or last spec. of batch) cast														
34	Total load on spec. (Date) (Age)														
35	" " " " " " 1st. spec.														
36	" " " " " " 2nd. spec.														
37															
38															
39															
40															

¹ Line 34. If more than a single specimen is cast from a batch succeeding lines may be used, one for each specimen per batch. If there are many specimens, a data sheet for specimens similar to that for Problem 19 may be needed.

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DESIGN OF CONCRETE MIXTURES (Trial Batch Method)

Data sheet No. 2. Calculations and results

Note: Some entries represent intermediate steps in calculating desired results. Main items are marked with an asterisk*. + Items usually required for job use.

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
*a Batch No.							from p. 1		1				2	3	4
*b Strength Specified (p.s.i.)							" " 1		3000				3000	3750	2250
*c " Actual							" " 1								
*d Slump specified (in.)							" " 1		6-7	2-4	0-1		2-4	2-4	2-4
*e " actual							" " 1								
1 Cem. wt. in batch (lb.)							" " 1		6.00				6.00		
2 F.A. " " " "							" " 1								
3 C.A. " " " "							" " 1								
4 Water " " " "							" " 1		3.84				3.84	3.84	3.84
5 Total wt. of batch															
6 Cem. abs. vol. in batch (cu. ft.)									L1 ÷ 196.6						
7 F.A. " " " "									L2 ÷ 165.4						
8 C.A. " " " "									L3 ÷ 165.4						
9 Water " " " "									L4 ÷ 62.4						
10 Abs. vol. materials in batch (cu. ft.)															
*11 Unit wt. neglecting air voids (lb. per cu. ft.)									L5 ÷ L10						
*12 " " observed									Compute from sheet 1 L32						
*13 Total abs. vol. constit. in unit vol. (†)									L12 ÷ L11						
*14 Cem. abs. vol. in unit vol. concr. (c)									(L13)(L6) ÷ L10						
*15 F.A. " " " "							(a)		(L13)(L7) ÷ L10						
*16 C.A. " " " "							(b)		(L13)(L8) ÷ L10						
*17 Water " " " "							(w)		(L13)(L9) ÷ L10						
*18 Air voids " " " "							(va)		1 - † = 1 - L3						
*19 Solidity ratio " " " "							(d)		L14 ÷ L15 + L16						
*20 Voids " " " "							(v)		1 - L19; also L17 + L18						
21 Cem. wt. in 1 cu. ft. concr. (lb.)									(L14) 196.6						
22 F.A. " " " "									(L15) 165.4						
23 C.A. " " " "									(L16) 165.4						
24 Water " " " "									(L17) 62.4						
+25 Yield cu. ft. concr. per bag. cem.									94 ÷ L21						
+26 Cem. per cu. yd. concr. (lb.)									(27) L21						
+27 F.A. " " " "									(27) L22						
+28 C.A. " " " "									(27) L23						
+29 Water " " " "									(27) L24						
+30 Cem. " " " (bags)									L26 ÷ 94						
+31 Water " " " (gal.)									L29 ÷ 8.34						
*32 a/c by abs. vol.									L15 ÷ L14						
*33 b/a " " "									L16 ÷ L15						
*34 b/bo " " "									L16 ÷ sheet 1 L8						
*35 v/c " " "									L20 ÷ L14						
*36 w/c " " "									L17 ÷ L14						
+37 w/c gal. per bag. cem.									L31 ÷ L30						
*38 Prop. by abs. vol.															
+39 " " weight															
*40 Strength-Econ. ratio									Lc ÷ L30						

and, initially, less than the probable final amount of aggregate should be used. When the desired mixture has been attained and all observations taken and recorded, a specimen (or specimens) will be cast from the batch as was done in Item 2c.

- b. Determine the cement-water ratios that should give the 25 per cent increased and decreased strengths, and compute the new weights of cement and fine aggregate to be used, checking these calculations with the instructor.
- c. Weigh out the materials for the two new batches, using exactly the same weights of coarse aggregate and water as were used in the base batch of Item 3a. Take and record observations of texture, slump, flow, and unit weight, and cast into specimens as before.
- d. Cap, number, and store the specimens in accordance with A.S.T.M. Designation C39-39, and test at 28 days (or other designated age). It is simpler, and at least as accurate, to measure the diameter of the molds than to measure the diameter of the specimens with calipers and scale. If the variation in the diameters of the molds in the closed position is not more than a few hundredths of an inch, the area for computing stresses may be determined from the mean of careful measurements of the diameters of all the molds. A black graphite crayon or even chalk is satisfactory for numbering specimens if reasonable care is exercised not to rub the markings. Either material can survive immersion satisfactorily. Place the specimen number on the molds when cast and on top of specimen before mold is removed.

G. Report.

1. *Results.*—Six sets of determinations were made, one for each of the three consistencies of the preliminary tests and one for each of the three batches of the final tests. Record the pertinent data on materials and batches as indicated on sample data sheet No. 1. Calculate the quantities, or such of them as the instructor designates, and record them on a data sheet similar to sample data sheet No. 2. Mention any unusual features or interesting results which are not readily apparent on the data sheets.

H. Supplementary Questions.

302. The following terms are used frequently in connection with the placing qualities of concrete mixtures. Discuss each group of terms briefly.

- a. Workability, consistency, and texture.
- b. Harsh, plastic, and fat.
- c. What are measured by slump and flow?

303. a. How may the consistency of a mixture be varied without varying the texture? Should this alter the strength?

- b. How may the consistency be varied without altering the water-cement ratio? Should this affect the strength or texture?
- c. How may the probable strength be varied without altering the workability (either consistency or texture)?
- d. How may yield be increased without loss of workability?
- e. Can yield be altered without altering the predicted strength?
- f. Can yield be altered without altering either consistency or predicted strength?

304. a. For a given water-cement ratio, which is the more economical—a stiff mixture or a thin one? Answer on the basis of the evidence from your studies.

- b. Why is the more economical mixture not always used?
- c. Is lack of economy the only, or even the major, objection to the use of the less economical mixture?

305. a. Which may be expected to stiffen a mixture most if added in equal amounts—cement, fine aggregate, or coarse aggregate?

- b. Does the Lyse rule for altering strengths at constant workability assume a difference between the stiffening power of cement and that of fine aggregate
 - (1) When the interchange of cement and fine aggregate is by weight?
 - (2) When the interchange of cement and fine aggregate is by absolute volume?
- c. Do you consider the Lyse rule to be basic or simply a convenient approximation?
- d. Within the range of application made in these tests how nearly constant did the workability remain as judged by the slumps secured?
- e. How might the validity of the Lyse rule be checked readily by a simple test at limiting values?

- f. Are any of the mixtures outlined in the suggested series of Chap. XI designed to supply such a check of Lyse's method at limiting values?
- g. If the limiting cases of Item *e* fail to produce mixtures of equal workabilities, how may the extent of the discrepancy be investigated?
- h. Should the valid range of Lyse's approximation be the same regardless of the fine aggregate used?

306. To vary the slump of a mixture, Dunagan (page 682 of Reference *m*, Chap. XI) states that a change of 0.005 in the value of *w* (absolute volume of the water in a unit volume of the concrete) will vary the slump by approximately 1 in.

- a. Should one expect such a rule to be general and precise? Explain.
- b. How well does it agree with the values of *w* and slumps secured in your trial batches?

PROBLEM 19

Comparisons of Concrete Mixtures and Curings

A. Object.

1. To compare different concrete mixtures on the basis of texture, consistency, and yield.
2. To investigate the influence of specified differences between mixtures upon strengths developed by specimens similarly cured.

3. To investigate effect of variation in age, curing, and moisture state at test on strengths developed by specimens which are initially similar.

B. Materials.—Unless the instructor indicates otherwise, these will be identical with those of Prob. 18.

C. Equipment.—Same as for Prob. 18. In addition, a small concrete mixer may be used if available and desired.

D. References.—Same as for Prob. 18.

E. Mixtures and Batch Variables to Be Studied.

These will conform to Series I, II, or III as outlined in Chap. XI (Art. 84) or to an independent series designated by the instructor. Regardless of the comparison being made, the proportions for the "base mixture" should correspond to those determined by the trial-batch technique of Prob. 18. Data to be taken on the batches will conform closely to the items indicated on sample data sheet No. 1 for Prob. 18, only such changes being made as are necessitated by differences in the particular variables introduced. The sequence and arrangement of the items to be entered on the laboratory-record sheet, as well as on the second sheet showing the calculations and results for the batches, are optional. Of course, the title on the sheet should indicate the series by number and title, and the upper column entries should be selected to indicate the nature of the investigation with a minimum of searching. The outline and objectives as covered in Arts. 84 and

85 should be mastered before any of the experimental work is started.

F. Specimens and Sizes of Batches.

1. *Size of Specimen.*—The size of specimen may be anything from an ordinary 6-in. by 12-in. standard cylinder to the smallest size of cylinder compatible with the maximum size of coarse aggregate used. A 6-in. by 12-in. specimen is suitable for aggregates up to 2 in. The 3-in. by 6-in. cylinder is excellent where the maximum aggregate does not exceed 1 in.

2. *Size of Batch.*—Use multiple-specimen batches sufficiently large, if possible, to permit all specimens of a given composition to be cast from a single batch. Design the batch for the actual volume of the specimens to be cast plus a 10 per cent allowance for wastage. The size of batch required depends on the size of specimen and on the number of duplicate specimens desired for the study of such differences as those of age, curing, and state of dryness when tested.

G. Allocation of Specimens.—If each batch contains fewer than eight specimens, one specimen should be allocated to each of the following treatments in sequence, for as many treatments as the number of specimens in the batch permits. If there are more than eight specimens in the batch (which is feasible if 3-in. by 6-in. specimens are used), specimens 9, 10, 11, etc., may be used to duplicate cases 1, 2, 3, etc., or other ages or curing conditions may be added at the discretion of the instructor.

Specimen No.

1. To be standard-cured and tested moist at 28 days.
2. To be stored in the dry air of the laboratory and tested dry at 28 days.

3. Same as No. 2, but to be immersed for a period of 12 to 24 hr. immediately prior to test at 28 days.
4. To be standard-cured for 18 days, stored in dry air for 10 days, and tested dry at 28 days.
5. Same as No. 4, but to be immersed for a period of 12 to 24 hr. immediately prior to test at 28 days.
6. Same as No. 1, but to be tested at 7 days.
7. Same as No. 2, but to be tested at 7 days.
8. Same as No. 7, but to be immersed for a period of 12 to 24 hr. immediately prior to test at 7 days.

H. Data to Be Secured on Each Specimen Subsequent to Fabrication.¹⁷

1. Weight as soon as mold is removed.
2. Weight at time of testing.
3. Weight at each intermediate change of environment or status such as just prior to immersing an air-stored specimen or upon removal of a specimen from moist storage.¹⁸ Specimens (or conditions) No. 3, 4, and 8 each require one intermediate weighing. Specimen No. 5 requires two intermediate weighings.
4. Ultimate compressive strength.
5. Percentage changes in weights from weight as removed from the molds.

I. Procedure.

1. *Preparation for the Test.*—Determine the weights of cement, aggregates, and water for all

¹⁷ To secure differences in weights which are significant, 6-in. by 12-in. cylinders should be weighed on scales that are fully sensitive to 0.01 lb., and the weights of 3-in. by 6-in. specimens should be to the nearest 0.5 or preferably 0.1 g. The Buffalo Scale Company of Buffalo, N. Y., produces a counter scale of 250-lb. capacity of excellent sensitivity which has beam graduations of 0.01 lb. These scales are well adapted to weighing 6-in. by 12-in. specimens for moisture differences, as well as to weighing out materials for batches. There are on the market several makes of metric balances, of 2-kg. capacity and over, which are sensitive to 0.5 g. or less. These are well adapted for securing differences in weights of 3-in. by 6-in. specimens. At the discretion of the instructor all weighings (Items 1, 2, 3, and 5 which follow) may be omitted.

¹⁸ Specimens which are dripping wet should be placed on a piece of toweling or burlap for a few moments prior to weighing to permit the free water to drain off. Surfaces of such specimens should be moist rather than either dry or very wet.

the batches which are to be cast, and check these with the instructor.¹⁹

2. *Fabrication.*—Weigh out the materials for the batch of the base mixture, which may be mixed either by hand or by machine. After making and recording the necessary observations, cast the concrete into specimens in accordance with A.S.T.M. Designation C39-39, Sec. 13. The other batches will be similarly mixed and cast.

3. *Capping, Storing,²⁰ and Testing.*²¹—Cap all specimens in accordance with A.S.T.M. Designation C39-39. Remove the molds, and weigh and store the specimens as required. Handle carefully to avoid any chipping that might influence weights. Test at the designated age.

J. Report.

1. Assemble and compute the quantities indicated on the illustrative data sheet No. 2 from the data on the materials and the batches, omitting only such items as the instructor may indicate.

2. Prepare a third sheet for the data that are to be secured on the individual specimens. Such a sheet is shown illustratively as data sheet No. 3.

3. Graph Sheet.

a. Prepare a graph sheet appropriate to the batch variables being investigated, plotting strengths as ordinates.

b. Plot a bar diagram showing the relative strengths, actual and percentage, for the different curings and ages, the standard-cured 28-day strength being taken as 100 per cent.

4. Conclusions.

a. In a few short statements summarize the results secured, offering any tentative conclusions that appear to be warranted.

b. Indicate whether or not the results are in accord with those expected, indicating

¹⁹ For untried proportions, especially those which represent limiting amounts of aggregate or water, it may be impracticable to determine all weights in advance, and it will be necessary to proceed cautiously by trial to avoid over-running the mixture desired.

²⁰ Specimens should be numbered and marked on top prior to removal of molds (which in turn should have been marked at time of casting). Ordinary chalk or a soft black pencil or crayon is satisfactory for marking if reasonable care is taken not to rub the mark. Such marks will survive moist storage.

²¹ See Chap. V on compressive testing, and the experiment and questions relating thereto, for more detailed consideration of capping, testing, and other items of importance in a compressive test.

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Name _____ Recorder (r) _____ Received _____
 Problem No. 19 Course No. _____ Operator (p) See Problem 18 for _____ Returned _____
 Date _____ Observer (b) representative data _____ Received _____
 Section _____ Computer (c) sheets No. 1 and 2 _____
 Squad No. _____ Kit No. _____ Helper (h) _____ Grade _____

DATA SHEET No. 3 ON COMPARISONS OF CONCRETE MIXTURES AND CURINGS

Laboratory data on weights of specimens and compressive tests.

(See Sheets 1 and 2 for data on the batches)

All specimens are 3-by 6-in. std. cylinders. Wts. in grams. Storage, curing and test conditions conform to those described in Sect. G.

	a	b	c	d	e	SPEC. NO. AND CURING AS DESCRIBED IN SECT. G.										o	
						1	2	3	4	5	6	7	8	9	10		
1	Date of test																1
2	Age at test (days)					28	28	28	28	28	7	7	7				2
3	Curing (described in G.)					Std.	Air	Air	Std.	Std.	Std.	Air	Air				3
4	Test condition					W	D	W	D	W	W	D	W				4
5																	5
6	Wt. as stored	Batch 1															6
7		2															7
8		3															8
9		4															9
10		5															10
11		6															11
12	Intermediate wt. Batch 1					—	—	—			—	—	—				12
13		2				—	—	—			—	—	—				13
14		3				—	—	—	(1)	(1)	—	—	—				14
15		4				—	—	—			—	—	—				15
16		5				—	—	—			—	—	—				16
17		6				—	—	—			—	—	—				17
18	Intermediate wt. Batch					—	—	—			—	—	—				18
19		2				—	—	—			—	—	—				19
20		3				—	—	(2)		(2)	—	—	(2)				20
21		4				—	—	—			—	—	—				21
22		5				—	—	—			—	—	—				22
23		6				—	—	—			—	—	—				23
24	Wt. at test	Batch 1															24
25		2															25
26		3															26
27		4															27
28		5															28
29		6															29
30	Ult. load (lb.)	Batch 1															30
31		2															31
32		3															32
33		4															33
34		5															34
35		6															35
36																	36
37																	37
38																	38
39																	39
40																	40

(1) Wts. upon removal from moist storage at 18 days
 (2) " " immersion 12 to 24 hours prior to test

FORM E DEPARTMENT OF THEORETICAL AND APPLIED MECHANICS IOWA STATE COLLEGE

Name	Recorder (r)	Received
Problem No. 19	Operator (p) See Problem 18 for	Returned
Date	Observer (b) representative data	Received
Section	Computer (c) sheets No.1 and 2	
Squad No.	Helper (h)	Grade
Kit No.		

DATA SHEET No.4-ON COMPARISONS OF CONCRETE MIXTURES AND CURINGS

Computed data on changes in weights of specimens and on compressive strengths.

(See Sheets 1 and 2 for data on the batches)

Specimens 3- by 6-in. cylinders. Areas of cross section assumed to correspond to the mean diameter of the molds which is 3.00 in. Area = 7.07 sq.in.

SPEC. No. AND CURING AS DESCRIBED IN SECT. G.															
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
						1	2	3	4	5	6	7	8	9	10
1	Age at test (days)					28	28	28	28	28	7	7	7		
2	Curing (described in G.)					Std.	Air	Air	S18A10	S18A9	Std	Air	Air		
3	Test condition					W	D	W	D	W	W	D	W		
4	Ratio to wt. stored (Intermediate wt.)			Batch 1	2	—	—	—			—	—	—		
5					3	—	—	—			—	—	—		
6					4	—	—	—	(1)	(1)	—	—	—		
7					5	—	—	—			—	—	—		
8					6	—	—	—			—	—	—		
9	Ratio to wt. stored (Intermediate wt.)			Batch 1	2	—	—	—			—	—	—		
10					3	—	—	—			—	—	—		
11					4	—	—	—	(2)	(2)	—	—	(2)		
12					5	—	—	—			—	—	—		
13					6	—	—	—			—	—	—		
14	Ratio to wt. stored (Wt. at test)			Batch 1	2	—	—	—			—	—	—		
15					3	—	—	—			—	—	—		
16					4	—	—	—			—	—	—		
17					5	—	—	—			—	—	—		
18					6	—	—	—			—	—	—		
19	Unit str. p.s.i.			Batch 1	2	—	—	—			—	—	—		
20					3	—	—	—			—	—	—		
21					4	—	—	—			—	—	—		
22					5	—	—	—			—	—	—		
23					6	—	—	—			—	—	—		
24	Str. % str. base			Batch 1	2	100.	100.	100.	100.	100.	100.	100.	100.		
25					3	—	—	—			—	—	—		
26					4	—	—	—			—	—	—		
27					5	—	—	—			—	—	—		
28					6	—	—	—			—	—	—		
29	Str. % 28-day std.			Batch 1	2	100.	—	—			—	—	—		
30					3	100.	—	—			—	—	—		
31					4	100.	—	—			—	—	—		
32					5	100.	—	—			—	—	—		
33					6	100.	—	—			—	—	—		

 (1) Upon removal from moist storage at 18 days.
 (2) " immersion for 12 to 24 hours prior to test

by specific reference the basis for any expectations.

K. Supplementary Questions.

307. Refer to the outline of Series I of Chap. XI. Assume that for the aggregate used, the trial-batch determination for the base mixture gives a value of $b = 0.40$.

- a. Determine and tabulate the values of c , a , b , and w for Mixtures 1 to 5, inclusive, if the interchanges between cement and fine aggregate are to be on the basis of absolute volume as indicated in the outline.
- b. Can a corresponding tabulation be made for Batches 6 and 7 on the basis of the information available?
- c. Tabulate the corresponding quantities by absolute volume if the interchanges between cement and fine aggregate are made in equal amounts by weight instead of by absolute volumes. Hold the cement-water ratio unchanged; assume specific gravities of cement and aggregates to be 3.15 and 2.65, respectively. Compare proportions of batches with those for Question 307a.
- d. Explain why the sum of the batch quantities in part *c* does not equal unity. Convert them to the unit volume basis and compare with Question 307a.
- e. Express the quantities secured for the interchange by equal weights in Question 307d as percentages of those for the interchange by equal absolute volumes in Question 307a and comment with respect to apparent relative importance of the differences in the quantities for the two methods.
- f. As a means of job adjustment
 - (1) Which basis of interchange is the simpler to apply?
 - (2) Which should be used?
- g. As was explained in Chap. XI, Batches 4 and 5 are simply manipulative batches for studying characteristics of limiting mixtures. Is it possible to judge whether or not these batches are likely to be workable without an actual trial?
- h. Discuss the usefulness and the limitations of the Lyse method for adjusting mixtures on the basis of your own experience with it.

308. The fact that a complete substitution of cement for fine aggregate as in Batches 4 and 6 of Series I stiffened the mixture of Batch 4 to the point of nonworkability (see Question 307g) indicates clearly that the fine aggregate is not the equivalent of cement in its water requirement and that Lyse's method is but a convenient approximation bound to be valid over only a limited range.

- a. Should it not be possible by comparing the relative water requirements for Batches 6 and 7 to evaluate the water requirement of the fine aggregate used in terms of the cement so that the method could be extended to cover substitutions over virtually the whole range of mixtures? Discuss from the standpoint of feasibility, the difficulties likely to be encountered and the limitations on use of the results secured.
 - b. When the interchange of cement and fine aggregate is on any basis other than equal parts by absolute volume, what change is bound to be made in such a diagram as that of Fig. 26?
 - c. Assume that the sand-cement equivalent (ratio of sand to cement to produce equal stiffening effects) for the fine aggregate of Series I is 2.0 by absolute volume. Compute and tabulate the values for c , a , b , and w . Mixtures 1, 2, and 3 are to be unchanged in strength (according to the water-cement ratio criterion). Plot on a diagram similar to Fig. 26, dotting in the lines corresponding to the one-to-one equivalents of Lyse.
 - d. As a practical means for adjusting or changing mixtures, is the use of the modification or extension of the Lyse method any less practicable than the one-to-one substitution that he recommended?
- 309.**
- a. According to the water-cement-ratio criterion for strength, which of the six batches of Series II should produce the strongest concrete?
 - b. If there were significant differences in the strengths secured for specimens similarly cured, indicate which of the differences between batches appear to have an influence upon strength.
 - c. Which batch
 - (1) Was strongest?

- (2) Was most economical?
 - (3) Had the highest value for the strength-economy ratio?
 - d. (1) Were the specimens from all batches of equally good appearance?
 - (2) If there were differences, were the worst appearing specimens the weakest and were the best appearing specimens the strongest?
 - e. Compare the mortar specimens of Batches 5 and 6 with the concrete specimens of Batches 1 to 4 on the basis of strength, economy, strength-economy ratio, and the changes in weight which occurred for similar storage during the curing periods.
 - f. How did the relative amounts of coarse aggregate in Batches 1 to 4 affect slump, texture, strength, economy, appearance, and strength-economy ratio?
- 310.** a. According to the water-cement-ratio criterion for strength which of the batches of Series III should produce the strongest concrete?
- b. Compare the mixtures of Series III on the basis of slump, texture, strength, economy, appearance, and strength-economy ratio.
- c. For Series III do there seem to be any important variations within the water-cement-ratio law? If so, state their nature and indicate the extent to which they seem to limit the range over which the law can be accepted as valid.
- 311.** a. Were the strengths secured for the various ages and curing and test conditions of the same relative magnitudes for the different series and batches?
- b. Were the effects of the various ages and curing and test conditions in agreement with the indications of the universal curing diagram of Fig. 24?
- c. Is a moist-cured specimen which has been exposed to dry air for a few hours prior to test, having become surface dry, to be considered as meeting the description "moist-cured, dry at test" as the term is used on Fig. 24?
- d. How long must an air-dry specimen be immersed in order to qualify as "wet at test"?
- e. For how long may an air-dry specimen be re-immersed before "resumed curing" may be expected to have a significant effect on the strength secured?
- f. Give reasons for the characteristic difference in shape between the diagram of Fig. 24 and that of Fig. 25.
- 312.** a. Name the essential requirements for quality-control²² concrete specimens.
- b. How should job-control as well as quality-control specimens be tested? Explain.
- c. Some drilled cores are received for test. They are of constant diameter but of variable height, are relatively dry, and the ends are not plane. What measures should be taken to make the tests as meaningful as possible?
- d. What routine precautions should always be taken in transferring specimens from the job to the laboratory for test or for storage and test?

²² See Question 286 for a discussion of quality-control and job-control specimens.

CHAPTER XII

EXPERIMENTAL AIDS IN STRESS ANALYSIS

90. Introduction.—Mechanics of materials is essentially a mathematical method for evaluating the stresses in simple structural elements. As has been demonstrated in the laboratory, the analyses give good results within the limits of stipulated assumptions and conditions. Straight beams of constant cross section, axially loaded tensile or compressive members, shafts of uniform circular cross section, and uniform columns are examples of members which may be analyzed by the methods of mechanics of materials.

If the members are nonuniform or contain abrupt changes in cross section, contain notches, holes, keyways, or other causes of stress concentration, are subjected to loads concentrated over small areas, or develop stresses above the proportional limit, some of the assumptions or conditions of the mechanics of materials are violated. Thus at practically all connections and at other points of load application, the true stresses may be expected to differ from the values computed by the ordinary stress formulas.

While some of these more complicated stress situations may be analyzed mathematically by simple extensions of the mechanics or by the theory of elasticity (1) (2),¹ others involve techniques which are too involved or too difficult for use in routine engineering design. For these cases empirical or rule-of-thumb methods of proportioning are likely to prevail. Many of the details relating to riveted joints, pin connections, gusset plates, fillets, and bearing devices are proportioned more on the basis of rules founded on experience and judgment than by rational design.

While rule-of-thumb methods, if based on an extensive background of experience, may give results which are both safe and reasonably economical, situations are constantly arising for which both mathematics and experience are inadequate to insure a reasonably well-balanced or even a safe design.

The extensive development of complicated mechanisms and high-speed machinery subjected

to both impact and fatigue has greatly increased the need for a better understanding of the relative magnitudes of stresses in areas of *stress concentration*, for these areas are the locations of incipient failure under both impact and repeated loading.

Several experimental aids have been developed to assist in the determination of stresses in statically indeterminate structures and at points of stress concentration. The aids may be grouped under three general headings: (a) observations on structures, (b) observations on models, and (c) analogies. The references given for each group are for the purpose of indicating where more complete information concerning the particular aid may be found. They in no sense constitute a bibliography.

91. Visual Evidence.—To an experienced critical observer, simple visual inspection of a structure will often yield considerable information regarding the merit of its design. The size, location, and direction of cracks, the rigidity of the structure, and its deflection under load, all are evidences of structural behavior which may give valuable information concerning the functioning of the parts. On the other hand, visual inspection may lead to erroneous conclusions, since cracks and other evidences of failure are often secondary effects, which are present only because of some basic but better concealed weakness. Visual evidence rarely yields quantitative relationships between load and stress.

92. Measurements of Reactions.—Many structures are externally statically indeterminate, *i.e.*, the reactions caused by the loads on the structure cannot be evaluated by the usual methods of statics. In such instances determinations of stress would be a routine matter if the unknown external reactions could be evaluated. Evaluation of the reactions on the actual structures may be accomplished by means of scales, calibrated jacks (3), proving rings (14), pressure cells, and similar load-weighting devices described in Art. 18.

93. Measurements of Strains.—If the stresses are below the proportional limit, they may be evaluated from measured strains as indicated in Art. 16 and the answer to Question 9. Different types of strain gages have been developed and

¹ Throughout this chapter numbers in parentheses indicate references on pp. 121–122.

used for such determinations. The strain-gage method is not suitable for evaluating stresses in regions of stress concentration because the strains are averaged over a gage length. However, strain gages with $\frac{1}{2}$ -in. or 1-in. gage lengths can often be adapted to situations where the localization of stress is not too pronounced.

94. Measurements of Deflections and Displacements.—As outlined in Art. 43, values for flexural stresses may be computed from measured deflections. The method will not yield exact results because of uncertainties introduced in the differentiation process, and the method can be applied only to flexural members, but under some circumstances its use may be justified for securing approximate results more easily than by other available means.

OBSERVATIONS ON MODELS

95. Use of Models.—The use of models as aids in structural analysis and design has become popular in recent years. The advantages of conducting preliminary studies on a relatively inexpensive model of an important structure before completing the final design of the structure are manifold. If the model is constructed and loaded under carefully controlled conditions in accordance with the mathematical requirements for similitude (15) (16) (19), the results may be used to predict the behavior of the full-size structure (the prototype) with a reasonable degree of accuracy.

96. Elastic Models.—Elastic models are those designed to be stressed below the proportional limit and to give results applicable to structures which are also to be stressed below the proportional limit. In general, they are geometrically similar to the prototype. References (17) to (25) list only a few of the many elastic model tests which have been reported.

The Beggs Deformeter gage (26) merits special attention because of its many possibilities of application in connection with elastic models. It consists of a set of carefully made end connections for use with celluloid or cardboard models of planar structures. The end connections are so designed that a known displacement or rotation may be introduced at the points of support of the model. The resulting displacements of the model then define the influence diagrams² for the reactions at

which the displacement or rotation is introduced. When used with measuring microscopes for evaluating the displacement, the Beggs Deformeter gage gives excellent results.

97. Plastic Models.—Plastic models are models intended for use in the plastic range of stress and are suitable for indicating magnitudes and directions of the maximum stresses in a member. For example, the mill scale, or iron oxide, on a piece of hot-rolled steel will peel or scale off when the stress in the material directly beneath reaches the yield point, and the lines formed by the scaling are in the direction of the maximum shearing stress (27) (44). Hence to determine the relationship between load and maximum stress in a member containing a notch, or other discontinuity, a model of the member may be made of hot-rolled steel and loaded. The load at which scaling starts will be the load which produces the yield point stress, the point at which scaling starts will be the point of maximum strain, and the direction of the lines of scaling will give information concerning the direction of the maximum stresses. In practice, a thin coating of brittle paint, whitewash, or cement paste may be substituted for the mill scale. If magnitudes of stress are desired, a control sample must be tested to determine the stress at which the brittle paint scales. In much the same way a polished metal will develop strain lines or Lüders' lines (1) (44) in the direction of the maximum shearing stress at definite stresses.

Some metals, such as soft copper or type metal, will develop, when stressed beyond the proportional limit, a permanent set proportional to the maximum strain. If models made from such materials are marked with a grid of fine lines, loaded above the proportional range, and unloaded, the distortion of the grid will give information regarding the distribution of stress. The same technique has been applied within the elastic range to rubber models, the distortion of the grid being observed while the model is loaded.

98. Brittle-material Models.—The maximum stresses at points of stress concentration may be evaluated from models made of brittle materials, or materials³ which have straight-line stress-strain diagrams practically to the ultimate. The technique for evaluating the stress-load relationship at

² An influence diagram for a reaction indicates the reaction resulting from a unit load located at any point on the structure.

³ Plaster of paris, or potter's plaster is a satisfactory material for the purpose. When well dried, its proportional limit practically coincides with its ultimate strength. Gray cast iron has also been used.

a notch in a beam, for example, consists in preparing a pair of models, one containing the notch and the other one similar except that it does not contain the notch. The two models are then loaded to destruction, and the loads at failure are noted. From the simple model the maximum stress may be computed. If the other model is of the same material, the ultimate strength is the same, and the relationship between the load on the member and the maximum stress is established. The brittle-material method applies only when the stress-strain diagram is a straight line to the ultimate, since the flexure formula, which is based on the assumption of a straight-line stress-strain diagram, is normally used for the evaluation of the stress in the control model. The brittle-material method has also been applied to a study of the stresses in slabs and other structural members in which the stress distribution is difficult to determine by purely mathematical methods (28) (29). In practice the results from several pairs of such models are usually averaged since an individual specimen may contain flaws, thus giving an erroneous result.

99. Photoelastic Models.—Within the past few years much attention has been directed to the photoelastic method of stress analysis. The method is excellent for indicating the areas of stress concentration, and with suitable measurements the magnitudes of the stresses at desired locations within the member may be evaluated.

The method is based on a recognition of the fact that some transparent materials such as celluloid, glass, and bakelite⁴ are double refracting when strained. Polarized light, when passed through a strained area of the model, will therefore emerge with two components. The two components, on being passed through a second polarizing element at right angles to the first, will reinforce or annihilate one another, causing black and white (or colored, if the original light is not monochromatic) areas or bands on the projected image of the model. The directions, and with supplementary measurements, the magnitudes of the stresses, may be evaluated from the position and the spacing of the lines. Points or areas of stress concentration are distinctly evident as areas in which the bands are close together or tend to converge.

⁴ Bakelite is generally regarded as the most satisfactory material because of its high optical sensitivity and because of the relative ease with which it may be shaped. There are, however, many types of bakelite only a few of which are satisfactory for photoelastic studies.

References (27) (30) (31) (32) (33) (34) (35) give or show details of the construction and operation of photoelastic equipment. Photoelastic studies have yielded highly satisfactory results in their application to many problems involving concentration of stress, the effects of which are difficult to evaluate by other methods. While seemingly the method is limited to axial or biaxial states of stress, two techniques have been evolved for extending the method to include triaxial stress situations (36) (37) (38).

ANALOGIES

100. Use of Analogies.—Some stress problems may be solved satisfactorily by the use of analogies, in connection with which models not similar to the prototype are usually employed. Any stress situation may be expressed in terms of a differential equation, which will yield a solution to the problem providing that it can be integrated and the constants of integration can be evaluated. In members having areas of stress concentration, the evaluation of the constant may become involved or impracticable. However, in some cases the solution is known to another problem which depends upon a differential equation of the same type, in which case the stress may be evaluated by use of the analogy to the known situation.

Highly satisfactory results can be obtained by the use of analogues if all the mathematical conditions are satisfied. Several analogies have been used to advantage in dealing with torsional problems.

101. The Membrane Analogy.—The elastic-membrane, or soap-film, analogy, introduced by Prandtl (39) but extended and used by Griffith and Taylor (40), may be used for evaluating torsional stresses in members of any cross section. It utilizes the similarity between the differential equation for the stress in any torsional member and the differential equation for an elastic membrane, with no resistance to bending, under normal pressure. In applying the analogy, a hole having the same shape as the cross section of the member studied is cut in a flat plate. The plate is fitted to form the top of an airtight box, and a soap film, or other elastic membrane, with virtually no resistance to bending, is stretched across the hole. The pressure within the box is either increased or decreased slightly, distending the membrane. The analogy indicates that the torsional stresses in the member are proportional to the slopes of the mem-

brane at the corresponding points in the cross section and that the torque required to produce a unit angle change in the member is proportional

in much the same way as the membrane analogy is used for stresses below the proportional limit. In using the sand-heap analogy a horizontal plate of



FIG. 29.—Plaster casts to illustrate membrane analogy.

to the volume between the membrane and the plate. The proportionality factors may be evaluated from the pressure and surface tension of the membrane, but it is usually more convenient to evaluate them from a similar membrane stretched over a circular hole in the same plate. Since the stresses in a circular shaft, corresponding to the circular hole in the plate, may be evaluated directly by means of the torsion formula, the proportionality factors may thus be determined readily.

The soap-film analogy affords a very convenient qualitative method of analysis, as well as giving quantitative values when measurements of slopes are taken. In many situations the regions of maximum stress may be determined without recourse to actual experimentation by simply visualizing the appropriate distended membrane. In Fig. 29 is shown a photograph of plaster casts of distended membranes. A membrane over a square opening representing a square shaft will have zero slope, indicating zero stress, at the center and at the four corners. The torsion formula indicates a maximum stress at the corners, but it is inapplicable to a noncircular section and is decidedly in error for this case. The maximum slope of the membrane will be at the mid-length of each side, indicating the points of maximum torsional stress. The membrane analogy also indicates immediately that the region of highest stress in a circular shaft containing a keyway is at the re-entrant corners at the base of the keyway.

The membrane analogy is valid only below the proportional limit (2) (27) (40) (41) (42) (43).

102. The Sand-heap Analogy.—For evaluating the torsional resistance of a mild steel shaft above the yield point the sand-heap analogy may be used

shape similar to the cross section of the member under investigation is covered with as much fine sand, or similar material, as will remain in place. The slope of the sand heap is proportional to the torsional stress in the member at the yield point (which is, of course, constant) and the volume of the sand supported by the plate is proportional to the torque required to produce a unit torsional strain in the shaft. The analogy is used to compare the torsional resistances of various cross sections when the entire cross section is stressed above the yield point of the material. However, it is obvious that no shaft will have all the material within it stressed above the yield point; hence, the sand-heap analogy and the membrane analogy may be used to supplement each other, the portion of the shaft stressed below the yield point being represented by the appropriate membrane (44).

103. Hydrodynamical Analogy.—Another approach to the evaluation of torsional stresses below the proportional limit is illustrated by the hydrodynamical analogy. In applying this method a container having the same cross section as the cross section of the torsional member under investigation is partially filled with a fluid of low viscosity and is rotated about the vertical centroidal axis. Information concerning the torsional stresses in the member may be gained from the shape taken by the fluid surface (45). Theoretically the analogy requires the use of a frictionless fluid, but water has been used with satisfactory results. Practically, the membrane analogy is more convenient to apply.

104. The Electrical Analogy.—The torsion formula applies only to circular shafts in a region of uniform diameter. For evaluating the torsional

stresses in shafts or other torsional members of varying circular cross sections, such as would occur near the end of a turned-down section, an electrical analogy has been devised (27) (41) (46).

In the electrical analogy the distribution of electrical current is measured in a model the thickness of which is made to vary as the cube of the distance from the edge corresponding to the center line of the shaft.

105. The Slab Analogy.—The similarity between the differential equation for a slab and the stress function for a slice of a structure subjected to plane stress or plane strain makes possible the solution of certain problems by measuring the displacement of a model slab supported and loaded to conform with specific mathematical requirements established by the analogy. The method has been used successfully in connection with the analysis of Boulder Dam and other large dams (18) (47) (48).

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SUPPLEMENTARY QUESTIONS

313. Mathematics is an old science.
 - a. Why is its recorded application to problems of design of relatively recent origin?
 - b. What is the relationship of materials testing to design?
 - c. Why, even at the present time, are only the simpler portions of major machines and structures "designed"?
 - d. Why are many types of structures and machines, such as most residences, farm buildings, many castings, and machine parts, proportioned by estimation rather than by analysis?
314. Comment briefly on the evolution of current design techniques
 - a. With respect to nature of the development.
 - b. The sequence in terms of men and natural laws.
315. Service performance constitutes the ultimate test of every design.
 - a. Does a good performance necessarily indicate a good design?
 - b. Do signs of distress in a structure or a machine part necessarily indicate the nature of its weakness?
 - c. Are results secured from observations on models necessarily valid indications of prototype behavior under similar loadings?
316. What relationship does the material presented in Chap. XII bear
 - a. To design?
 - b. To materials testing?
317.
 - a. Classify the several methods or devices mentioned in Chap. XII according to whether they apply to members in the elastic or the plastic range of stress.
 - b. Which of the methods or devices are especially well adapted to demonstration use? Give reasons.
318.
 - a. Explain briefly the qualitative indications that can be recognized readily, by inspection,
 - (1) From a photoelastic model.
 - (2) From membrane or soap film.
 - (3) From a sand-heap model.
 - b. Which, if any, of these methods are limited to qualitative determinations?

319. Indicate limitations which apply to each of the following items:

- a. Characteristics of material suitable for models for photoelastic studies.
- b. Essential property for the membrane (soap-film) method.
- c. Plaster suitable for use with the brittle-material method.

320. a. Distinguish between a model and a specimen.

- b. The "analogies" could be classed as "dissimilar models." Would this be a rational classification?

321. a. Name a few well-known recent cases in which tests were made

(1) On full-size structure.

(2) On models of the structure.

- b. Cite a few cases in which full-size units or models were tested for purposes other than for stress analysis.

322. Why are supplementary aids in stress analysis of much greater importance now than they were a few years ago?

323. The mathematical analysis of structures and structural members, as based upon statics, the

properties of the member, and the geometry of the structure, is now and will probably continue to be the primary method for stress determination. Is it correct to consider this method

- a. Exact for determinations within its accepted range of application (within the usual assumptions and conditions)?

- b. As the standard with which determinations by other methods should be judged?

324. What incident brought the membrane analogy of Prandtl into prominence?

325. Figure 29 shows some plaster casts illustrative of the soap-film or membrane analogy. A cast was made by stretching thin rubber over an aperture of the desired shape, this being the bottom for a mold in which several inches of thin plaster paste was poured. The weight of the plaster distended the rubber, giving the bulge corresponding more or less to a protruding bubble.

Which, if any, of the limitations relating to the membrane analogy were violated by this technique? If you contend that there were violations, do they necessarily invalidate the apparent indications of the models?

APPENDIX A

ANSWERS TO THE SUPPLEMENTARY QUESTIONS . . . . .	125

Chapter I

(See p. 25 for questions.)

Testing, Testing Equipment, and Testing Observations

1. *a.* Standards comprise those specifications and methods of test that have been formally adopted by the Society after approval by the membership in a letter ballot.

Tentative Standards represent the latest thoughts and practices and prior to adoption as standard are published as tentative by the Society on the recommendation of the committee concerned.

- b.* A70-39 is a standard relating to ferrous metals; B70-39 relates to a nonferrous metal.

E4-34T is a Tentative Standard issued in 1934. E4-36 is the Standard which superseded it in 1936. The prefix E indicates that they are probably either "Methods of Test" or "Definitions of Terms."

A41-36 is the 1936 version of Standard A41 which was adopted first in 1912 as A41-12 and was subsequently revised in 1913, 1918, 1930, and 1936.

C18-41 and C19-41 are consecutive standards of the C group that follow one another in order of initial formulation. The serial number of a Standard gives no clue to its nature or content.

- c.* Supplements that contain all new or revised Standards and Tentative Standards are issued in the intervening years (1940 and 1941, for example). These should be consulted for current revisions and changes in status. Standards and Tentative Standards are always subject to revision, replacement, or withdrawal.

d. No.

2. Friction of the ram and leakage past the ram are two sources of inaccuracy not present in either the lever system or the pressure cell or capsule.

3. See diagrams in text. Partially answered under No. 2 above.

4. No. Actually there may be some weaving or irregularity of the screws tending to vary slightly the rate of load application, and in the hydraulic machine the pumping of the liquid may tend to produce similar effects. Under usual conditions probably neither action is an important source of inaccuracy.

5. Yes. If the knife-edges of a lever system are kept sharp and clean to prevent sluggishness, such a system can be very accurate; it is not subject to changes of calibration because the lengths of the lever arms remain constant under usual conditions. The less expensive forms of hydraulic-weighing systems have less constancy of calibration because of variation in ram friction, leakage, etc.

6. *a.* Pressure gage connected to the liquid in the jack.
b. Applying the jack through a calibrated spring. A less simple and less common method would be to apply the jack through a pressure capsule or through a friction-tape arrangement.
7. *a.* Errors in lengths of lever arms, sluggishness due to dirty or dulled knife-edges, personal factor involved in "balancing the beam" with a hand-operated weighing system.
b. Friction of the ram, leakage past the piston, inaccuracies, and variability of the pressure gage.
c. Leakage in the system, temperature effects if the dial is not provided with an adjustable scale, and air in the system. It is essential that the proper clearances be maintained by keeping the right amount of liquid in the system consisting of capsule and gage. Correctly calibrated and used with high-type pressure gages, this constitutes an extremely accurate load-measuring device.
d. Little chance for errors beyond those from knife-edge friction and errors in manufacture and calibration.
8. Impact strains develop rapidly, and the inertia of moving parts may introduce appreciable error in measurements of such strains. The lighter the parts, the less will be the effect of inertia that they develop at a given acceleration of movement.
9. *a.* No, but it is required in the cases of biaxial and triaxial stress.
b. In the mechanics of materials it is shown that the principal stresses¹ at any point in a material are equal to

$$S_{\max.} = \frac{S_1 + S_2}{2} \pm \sqrt{\left(\frac{S_1 - S_2}{2}\right)^2 + S_s^2}$$

in which S_1 and S_2 are the normal stresses on two orthogonal planes and S_s is the shearing stress on the planes. Thus it is evident that, to evaluate the principal stresses at a point, the magnitudes and directions of three stresses at the point must be known. Similarly, in order to determine the principal strains, from which the principal stresses may be computed, it is necessary to measure the strain in three directions at the given point. Since it is easier to measure a normal strain than a shearing strain, a third normal strain is usually substituted for the

¹The principal stresses are the maximum and minimum normal stresses which exist on any planes through the point. The shearing stress is zero on the planes on which the principal stresses act.

shearing strain. The measurement of a fourth strain to serve as a check is often desirable.

The group of strain readings on overlapping

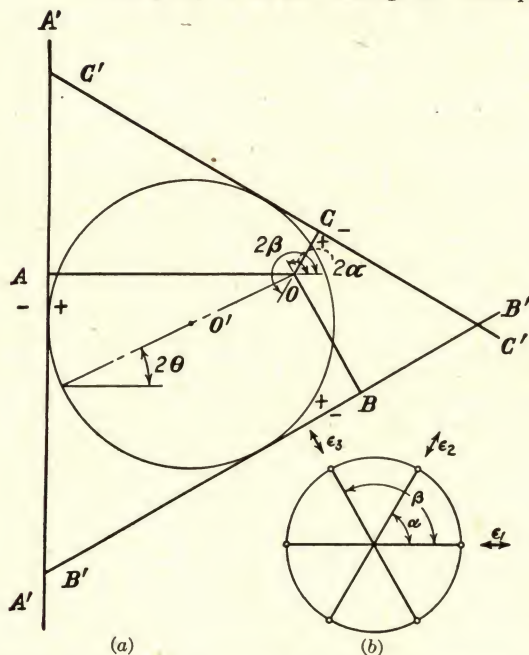


Fig. 30.—Graphical determination of principal strains.

gage lines is called a *rosette*. If three strains are measured, they are usually, although not necessarily, taken at 60 deg. from each other, as indicated in Fig. 30a. If four strains are measured, they are usually taken at 45 deg. A convenient graphical solution² for the evaluation of the principal stresses from the measured strains in a rosette is illustrated in Fig. 30b.

From any point O, using the direction of gage line No. 1 as the x direction, lay off, in the negative direction, the line OA representing the strain ϵ_1 to some scale, and draw the line $A'AA'$ perpendicular to OA. If the strain ϵ_1 is tensile, label the OA side of $A'AA'$ as positive and the opposite side negative. From the positive end of the x axis lay off the angle 2α , and in the negative direction from O measure the distance OB to represent the strain ϵ_2 . Draw $B'BB'$, and label the side BO positive if ϵ_2 is a tensile strain. The line OC is drawn to make an angle of 2β with the x direction and the distance OC scaled to represent the strain ϵ_3 .

Construct a circle tangent to $A'A'$, $B'B'$, and $C'C'$. Four such circles are possible. The correct one is the one which is tangent to all three lines on their positive sides, or tangent to all three on their negative sides. That is, if ϵ_2 were negative, the circle would be drawn on the opposite side of $B'B'$.

Draw the diameter DE through O. The distance DO represents, to the same scale that was used in plotting the strains, one principal strain

ϵ_u and OE , the other principal strain which is normal to ϵ_u . The angle 2θ , which DE makes with the x direction, is twice the angle θ which the direction of the principal strain (in the u direction) makes with the x direction.

The principal stresses may be found from the principal strains by the well-known relationship between stress and strain for biaxial stress.

$$S_u = \frac{E}{1-m^2} (\epsilon_u + m\epsilon_v) \quad \text{and} \quad S_v = \frac{E}{1-m^2} (\epsilon_v + m\epsilon_u)$$

in which S_u is the principal stress in the u direction (making the angle θ with the x direction), S_v is the principal stress in the v direction, ϵ_u is the principal strain in the u direction, ϵ_v is the principal strain in the v direction normal to the u direction, E is Young's modulus, and m is Poisson's ratio.

10. About 0.4 per cent.
11. a. Plus or minus 2 g.
b. Plus or minus 0.15 lb. or 2.4 oz.
c. Plus or minus 0.25 lb.
d. Fairly sensitive.
12. a. 200 sec. ($3\frac{1}{3}$ min.)
b. 2 in.

Problem 1

(See p. 27 for questions.)

Study of a Lever-type Testing Machine

13. a. (1) Inaccuracy of measurements of lengths of levers, especially where access was difficult.
(2) Inaccuracy in weighing the poise.
b. Measuring the lengths of the levers gives a positive result as accurate as the measurements permit. Determining the ratios from weight of poise involves the assumption that the beam reading gives a correct indication of the maximum load. The ratio of capacity load to weight of poise may be said to give an indication of the apparent multiplication ratio rather than constituting a valid determination. The indication may or may not be more nearly correct than are the results from the determination, depending on the relative accumulative effects of the errors or uncertainties involved.
14. Yes. In a compression test the specimen bears directly on the platen, and in a tension test the load is carried to the standards which bear on the platen. Lever scales can weigh only those forces which bear down upon them.
15. No. The platen is supported upon a dual lever system, each part of which has the same multiplication ratio.
16. No. The respective arms expand in proportion to their lengths.
17. No. Under normal conditions the locations of fulcrums and knife-edges are not subject to change.
18. a. The load is less than that given by a reading of the beam at the poise.
b. The load is more than the poise indicates but is in general otherwise unknown. Obviously such a

² As far as the authors know, this method originated with Dean H. M. Westergaard while he was teaching at the University of Illinois.

situation involves the hazard of possible overload and breakage.

19. One inch divided by the multiplication ratio.

20. The block of iron is rigid and can support a high load with very slight deformation. Only a very small movement of the head is required to jump the load from zero to the capacity of the machine or over. A considerable movement of the head is required to build up a 5000-lb. load on the spring, and the wood also offers a substantial cushioning, which insures a gradual increase of load as the head moves downward.

21. In a screw-gear machine the resistance to movement is largely that of the friction between the screws and the nuts at a given instant. The resistance to motion is nearly the same for movement in either direction.

22. No. The knife-edge approximates a segment of a cylinder of zero radius, and the frictional resisting torque that can be developed is very low. The frictional torque developed by a pin is much greater, even when well lubricated, because of the relatively large radius arm of the frictional force. In addition, even well-lubricated bearings tend to "freeze" under high pressures. The knife-edge insures low frictional resistance (if clean and sharp) besides definitely fixing lengths of levers.

23. The trend is away from the lever-type weighing system with manually operated poise and toward the various forms of self-indicating load-measuring devices. The manually operated poise introduces an objectionable personal factor besides being relatively cumbersome. While various types of pressure cell and hydraulic weighing systems have been introduced in recent years and are widely used, the lever system continues to be recognized as satisfactory, the only pronounced trend being away from the manual operation.

24. a. No. A special weight must be attached to the scale beam, this weight to remain fixed in its proper position as long as the smaller poise is in use.

b. In the zero position neither poise is at the fulcrum of the beam, and the added weight is to compensate for the effect of difference between the weights of the two poises when at the zero position. Without the added counterweight the beam would obviously be out of balance in its zero position unless weight was added. The adjustment required is much more than is possible with the regular counterweight provided for adjusting the beam to the zero position of the poise.

c. No. The lengths of all levers remain unchanged.

25. a. The load balanced by the supplementary weight equals the normal capacity of the machine, and the total load is given by adding the beam reading to the normal capacity. The range is from normal capacity to twice normal capacity.

b. No. With the weight in place balance can be secured at no load below normal capacity.

c. No.

d. The added weight simply does what the poise would do when at its maximum-load position.

e. From zero load to $\frac{1}{10}$ normal capacity.

Problem 2

(See p. 28 for questions.)

Calibration of a Testing Machine

26. Answer varies with type of machine calibrated. See text.

27. a. Standard weights.

b. Proving levers.

c. Elastic calibration device.

d. Comparison method.

e. Discussion of methods may be found in A.S.T.M. Designation E4-36.

28. Under Elastic Calibration Device.

29. See data.

30, 31, 32. Consult A.S.T.M. Designation E4-36 and Chap. I.

33. a. Reading is too low.

b. Reading is too high.

34. Yes. The greater the acceleration of load, the greater will be the tendency toward inertia effects.

35. Machines in which the load-indicating mechanism is relatively massive are most subject to inertia effects.

36. Qualitatively there is no difference. Each is a measure of the response or lack of response to change of load. Sluggishness represents lag; sensitivity, in a sense, represents readiness of response.

Problem 3

(See p. 31 for questions.)

Study of a Strainometer

37. a. Primarily errors of measurement.

b. Play in screws and only incidental errors of manipulation and observation, except such inaccuracies as existed in the strainometer dial and the dial used as the standard of comparison.

38. The calibrator method.

39. Answer would vary with type of compressometer used.

40. If plane of attachment to specimen is midway between plane of hinge and plane of dial, the dial movement is twice the change in length of specimen between the yokes.

41. Average movement of the dials equals the actual shortening of the specimen. The one-dial averaging type is simplest to use. The three-dial arrangement is the best for careful work. The readings on the three dials give a complete picture of the shortening. If the three readings are equal, all elements of the specimen are shortening equally; if unequal, the strains are not equal and the plane of one yoke is tilting with respect to the plane of the other yoke. The two-dial arrangement will usually show whether or not the strains are uniform but is insufficient to define the relative aspects of the planes of the yokes. (Three points determine a plane.)

42. a. If the gage length were 6 in., the error would be $\frac{1}{600}$ or about 0.17 per cent.

b. Percentage error would vary with the total strain being measured. If the total strain were 0.05 in., the error would be $\frac{1}{3}$ or 20 per cent.

43. d, e, f, g, h. These are the only properties which involve actual deformations. Properties depend-

ent solely upon loads are independent of the amount of strain.

44. No. All lengths are affected proportionately. The slight change in the gage length would be negligible even if the specimen were not similarly affected.

Chapter II

(See p. 37 for questions.)

Properties of Materials

45. See text.

46. *a.* Strength of a member is expressed as the total load it will resist (expressed in pounds for tension or compression). The strength of a material is the load it will resist per unit area (expressed in pounds per square inch). The strength of a given beam may be designated as the total load (pounds) it will carry on a designated span or as the bending moment (inch-pounds or foot-pounds) it can resist. The strength of the material is the stress that the most stressed fibers can develop (pounds per square inch).

The strength of a torsional member is expressed as the torque it can resist (inch-pounds), and the torsional or shearing strength of the material is the maximum torsional unit stress (pounds per square inch) which the material can develop.

b. Toughness of member is expressed in terms of total energy (inch-pounds) and modulus of toughness of material in terms of energy per cubic inch (inch-pounds per cubic inch).

47. See text.

48. See text.

49. See text.

50. Only the mild steel has a yield point.

51. *a.* The yield point of mild steel is raised by stressing it above its initial yield point. When a bar is stressed above the yield point and unloaded, the unloading curve will normally be a straight line parallel to the initial tangent of the stress-strain diagram. When the bar is again loaded, its stress-strain diagram will retrace the previous unloading curve continuing as a straight line to the previous maximum stress, at which stress there will be a new yield point, but the extent of the yielding will be less than at the original yield point. Successively higher cycles of loading will increase the yield-point stress and reduce the amount of new yielding until, with sufficiently high application of stress, no yield point will be distinguishable.

Cold-worked steel has usually been subjected to sufficiently high stresses during the manufacturing process to obliterate the yield point.

b. Unannealed cold-drawn steel does not have a yield point for the same reason that cold-worked steel in general has no yield point. Annealing will restore the yielding action, the degree of restoration depending upon the extent of the annealing. Full annealing will restore the steel to practically its original condition, there being only a slight residual increase in the yield point.

52. No. See text.

53. *a.* Pounds per square inch.

b. No units (a ratio).

c. Inch-pounds per cubic inch.

d. Stiffness is high.

e. Redundant, units unnecessary.

f. Omit either "percentage" or "per cent."

g. Pounds per square inch.

h. Pounds.

i. Brittle materials cannot be tough; they lack the necessary ductility or deformability.

j. Resilience is an elastic property and as such is not indicative of ultimate properties such as strength and ductility.

k. "Stressed" instead of "strained."

l. Timber has no yield point.

54. *a.* 1 kg., per sq. cm. = 14.22 p.s.i. = 0.968 atmosphere. One atmosphere is 3.2 per cent more than 1 kg. per sq. cm.

b. 1 p.s.i. = 0.0703 kg. per sq. cm.

1 in.-lb. per cu. in. = 0.0703 cm.-kg. per c.c.

(1) 29,000,000 p.s.i. = 2,040,000 kg. per sq. cm.

(2) 41,000 p.s.i. = 2880 kg. per sq. cm.

(3) 24 in.-lb. per cu. in.; 1.687 cm.-kg. per c.c.

(4) 26 per cent = 26 per cent.

(5) 0.21 = 0.21.

(6) 0.2 per cent = 0.2 per cent.

(7) 600 p.s.i. = 42.2 kg. per sq. cm.

(8) 12,000,000 p.s.i. = 844,000 kg. per sq. cm.

(9) 15,000 in.-lb. per cu. in. = 1055 cm.-kg. per c.c.

(10) 20,000 lb. = 9072 kg.

55. *a.* One-half.

b. Equal.

56. *a.* Zero.

b. 0.50. This can be readily demonstrated by calculation.

c. 0.00 and 0.50.

d. Poisson's ratio for rubber is approximately 0.50. The authors know of no well-authenticated determinations that fall as low as 0.10. Materials like concrete and plaster of paris have lower values of Poisson's ratio than do the metals.

e. Higher. As stress rises above the proportional limit, most materials tend to deform more and more nearly at constant volume.

f. The value would be lowered. The lateral strains are much smaller than the longitudinal strains, and more sensitive strainometers are required to secure relatively reliable lateral data. Doubtless the abnormally low values reported for Poisson's ratio of concrete as secured from some of the earlier tests can be explained on the basis of imperfections in the lateral strainometers which were used.

57. *a.* Under load the wires tend to straighten, and not all the elongation of the cable is the result of actual stretching of individual wires. This apparent added deformation gives a lower value for *E*.

b. The old cable has been well stretched through use and much of the added available slack has been lost.

Chapter III

(See p. 40 for questions.)

Evaluation of Properties from Load-displacement Data

58. Results given on Fig. 16.
59. a. Yes. Methods essentially identical.
 b. Method *c* is simplest and requires no calculation other than shifting the decimal point.
 c. No. Value of *E* is a function of the slope which is the same at *C'* as at *C*.
 d. No. Errors of plotting and reading constitute unnecessarily large percentages of the values being read (see Art. 40).
60. a. The value for *E* so determined would be a function of the slope of a line from 0 (of Fig. 16) to the plotted point. The method disregards the effect of the 00' correction and also the effect of the amount by which the plotted point misses the mean line 0'A. A point so selected at random might be an erratic value so far from the average as to be rejected if plotted so that this could be recognized.
 b. No. The averaging of all values would substantially reduce the errors due to inclusion of erratic values, but it would fail to take account of the 00' correction.
 c. This amounts to expressing *E* as a function of the slope of a line from 0 to the selected value, as *A*, instead of the slope 0'A or 0B.
61. a. The areas of the two triangles are equal because their bases and altitudes are equal.
 b. $OPQ = \frac{1}{2} (OQ)(PQ) = \frac{1}{2} \epsilon S = \frac{1}{2} \frac{S^2}{E}$.
 c. Yes. 0'Q' = 0Q.
62. a and b. The error in the numerical value of the modulus of resilience and the modulus of toughness is comparable, but the percentage error is less for toughness because of the much larger value of the modulus of toughness.
 c and d. Similar reasoning applies.
63. Any property dependent upon strain would be affected by the error in strain caused by ignoring 0'0. Yield strength and Johnson's apparent elastic limit involve strain measurements in their evaluation.
64. a. Take θ at some even decimal or multiple of *K* since θ and *K* can be canceled making $E_s = T$ except for correction for the decimal point or for the multiple which was taken.
 b. See text.
 c. Yes, except that *K* = unity.
65. Yes.

Chapter IV

(See p. 43 for questions.)

Tensile Tests

66. Decreased, because of stress concentration at the grip and tendency to bend.
67. Proper gripping and alignment promote freedom from localized secondary effects such as those from bending

and crushing near the grips. Axial tensile loading is assumed to exist, and, if the resistance is decreased because of more complex or more severe stress situations, the results are obviously misleading. It is not possible to compute accurately the relative influence of secondary effects, and it is important that they be eliminated so far as possible.

68. Crossed knife-edges have the greatest freedom from restraint because they can develop but little frictional torque. The friction developed at surfaces of spherical segments (which even for well-lubricated surfaces is considerable at high pressures) offers a substantial torsional resistance to adjustment because of the radius arm upon which it acts. The spherical segment of the 1-in. radius offers the greatest restraint because of its longer radius arm.

69. a. Less.
 b. No. The curvature increases as load is applied.
70. See text.
71. a. If only the strength is desired, a relatively short gage length may suffice, but, if strains are to be measured, an appreciable gage length is required. With the longer gage lengths the specimen is better able to adjust itself to incidental misalignment. The source of the specimen and the manner of fabrication may have an important bearing on gage length.
 b. In testing metals (A.S.T.M. Designation E8-40T) and timber parallel to the grain (D143-27) strains are often measured in order to evaluate the modulus of elasticity or other properties. Several of the standard specimens provide for gage lengths of 6, 8, or 10 in. All are easily available in such lengths.

Only the ultimate strengths are observed on most of the other specimens listed and a short gage length suffices. Because of their brittleness and lack of bending resistance specimens of materials such as gypsum and porcelain would be difficult to mold and handle if the gage lengths were much longer. The cast-iron tensile specimen is to be machined from a broken fragment of the transverse specimen which places a definite upper limit on its length. There are other reasons for some of the dimensional choices no doubt, while in other cases there is no special reason for the selection of the gage length specified.

Problem 4

(See p. 44 for questions.)

Commercial Tensile Test of Steel

72. a. The apparent strength would be less because the lugs are counted as if they are effective cross-sectional area, giving a larger apparent area for the deformed bar than it actually possesses at minimum cross sections. This makes the stress appear to be less than it actually is at the minimum section.
 b. Every property which depends on stress, such as Young's modulus, modulus of resilience, and modulus of toughness, is affected. The correctness of the values found for elasticity, percentage

- elongation, or percentage reduction of area is not affected.
- c. The manufacturing tolerance is narrowed on strength and unaltered on ductility. This aspect is covered rather fully in a discussion (*Proc. A.S.T.M.*, Vol. 34, Part I, p. 84, 1934).
73. a. 4.02 per cent for error of 1 oz.
 b. 0.16 per cent for error of 1 g.
 c. Same as parts *a* and *b*; stress varies with area.
 d. For 1 oz., 0.8 in.; for 1 g., 0.011 in.
 e. Decreases.
 f. The same.
 g. 0.35 per cent for the 1-in. square bar; 1.41 per cent for the $\frac{1}{2}$ -in. square bar.
 74. a. Use results from the test.
 b. The reduction in area of a ductile bar is a secondary phenomenon that occurs mainly after the ultimate load has been passed. Strengths need to be specified upon the basis of the area of the bar as manufactured since that is the only area that is known and measurable at the time of purchase. Moreover, a bar is used to carry a maximum load (not stress) which is based on its original or nominal area.
 75. The ultimate strength is always based on the actual original dimensions in order to determine the unit resistance of the material. Limiting tolerances of dimension (as determined by permissible weight variation) protect the consumer in his use of the nominal area in design.
 76. Most of the elongation of the fractured bar occurs in the immediate neighborhood of the fracture. This results in a much larger percentage value when it is averaged over 2 in. than when averaged over 8 in.
 77. a. An upper limit is set on the strength as a supplementary check on ductility and also as a check on the grade or quality of the steel.
 b. According to the requirements set forth in A.S.T.M. Designation A15-39, Table I, there is apparently no recourse but to reject the material on the basis of excessive strength even if all other requirements are met satisfactorily. This appears to most persons to be unreasonable, since few would argue that strength is other than a desirable quality. The answer probably is that the case is mainly hypothetical, since only rarely would a bar be found that was sufficiently ductile to pass if its strength were so great as to disqualify it; that if such a bar or lot of bars were found, it would be so freakish as to be questionable. Regardless of whether or not the requirement is a reasonable or logical one, the answer to the question appears to be "yes."
 78. a. Empirical.
 b. As long as strength requirements are met, the greater the ductility the better. Apparently those formulating the specification failed to feel that excess ductility introduces a hazard comparable to that of excess strength.
 79. a. Excess sulphur makes steel "hot short," or brittle when hot, and phosphorus makes the steel "cold short," or brittle when cold. In storage and under job conditions steel reinforcement is subject to subfreezing temperatures with the consequent breakage hazard. No job conditions entail the hazard of temperatures high enough to make hot-short breakage probable.
 - b. The limits are set to conform to what are possible of attainment under good commercial practice without increasing manufacturing costs unduly. If 0.10 per cent of phosphorus is not too much for steel manufactured by the acid-bessemer process, it should not be too much for either the open-hearth or the electric furnace. Thus, while the differential is illogical, it is of long standing, and all parties concerned seem to be satisfied with it. Many of the minor clauses written into specifications come as the result of hunch or compromise rather than of logic and may remain unrationalized indefinitely if the interest of neither consumer nor producer is affected sufficiently to produce dissatisfaction. Bessemer steel may be slightly higher in phosphorus than the other two kinds, but apparently the difference is of no competitive significance, for the two appear to be used for concrete reinforcement interchangeably.
 80. Tests have shown that all diameters of bars do not react alike to the bend test, and the differences specified for radius and angle of bend represent an empirical effort to compensate for the variable influence of bar type and bar diameter.
 81. See A.S.T.M. Designation A41-36.
 82. a. The lateral pressure of the grips produces an axial elongation due to the "Poisson's ratio effect," and this, added to the elongation near the faces of the grips from the direct tensile load, usually produces a greater intensity of surface deformation between the grips than at any other point along the bar. This first local scaling usually does not extend very far inside the faces of the grips because the tension in the bar diminishes rapidly through transfer of load into the grips.
 83. To be answered on the basis of the data secured. In general, small punch marks seem to exert no discernible influence on the load which a bar of ductile steel can carry or on the location of fracture. The effect of such factors as local roughness and grip conditions increases with hardness of steel. The harder and more brittle the steel, the less is the opportunity for a ductile redistribution of local effects during the course of the test.
 84. a. No.
 b. See text and reference.
 c. A bar of brittle material will usually fail near the grips if not turned down in the central portion, probably due to the bending stress concentration which develops in the vicinity of restraint. Another possible contributing factor is the fact that a somewhat greater tensile strain occurs near the faces of the grips as was pointed out in the discussion of Question 82a.
 d. A bar of ductile material rarely fails near the grips. The bending adjustment can occur with practically no serious localization of stress. This explanation is not sufficient, however, to account fully for lack of failure, but such additional

explanations¹ as appear to be plausible are somewhat involved.

85. No. The increase in distance between the testing heads includes not only the elongation of the specimen but also the deformation of the screws and the testing heads and all the slippage and lost motion that occur in the grips. The effect of slippage is relatively large with wedge grips because slipping occurs between the heads and the grips as well as between the specimen and the grips.

86. See text (Chap. III, Art. 41).

87. a. Modulus of toughness.

- b. Inch-pounds per cubic inch (see text, Chap. II, Art. 35).
- c. The modulus of toughness is represented by the area under a curve, with stress as the ordinate and strain as the abscissa. Toughness may be thought of, therefore, as the summarized product of stress and strain to failure. Mild steel has high toughness because of its moderately high strength and great capacity for taking ductile strain. Hard steel may have two or three times the strength of mild steel, but its strain is so limited that its toughness is relatively low. It is resilient rather than tough. Cast iron also lacks toughness because of its low deformability prior to fracture.
- d. Toughness is in energy or work units and should represent the capacity for resisting impact loads (shock or energy loading). Because of differences in behavior contingent on rate of application of load, as well as the difficulty in getting an energy load distributed uniformly throughout a member or a specimen, the modulus of toughness (determined from gradually applied static loading) is at best only a crude index to probable or possible impact resistance. The impact or shock energy that can be absorbed may be expected to differ considerably from what the modulus of toughness might indicate.

88. a. and b. Determine from data of test. These results emphasize the highly localized distribution of work of rupture under the conditions of static testing. Under dynamic testing some of the phenomena differ considerably from those observed here (the necking down may not occur), but the distribution of the energy throughout the specimen, and especially the distribution of energy between the specimen and the supporting and straining mechanisms, is even more uncertain than it is for the static loading.

89. a. Determine from data of test.

- b. The entire area under the stress-strain diagram.
- c. Yes. Such a procedure would insure approximately equal values for modulus of toughness regardless of the gage length. Under current practice the relatively large area which lies beyond the ultimate in the stress-strain diagram for a ductile material adds considerably to the value

secured for the modulus of toughness. The extent of the addition is much greater for the 2-in. gage length than for the 8-in. gage length, for reasons apparent from the discussion of Question 76. By analogy it is obvious that the ductility should also be taken as the percentage elongation to the ultimate, although the well-established practice of expressing elongation as a percentage in 8 in. or in 2 in. removes in some measure, at least, the need for a change in this regard.

90. a. No. The weight would have started falling at the ultimate, and the bar would have been ruptured in one continuous operation.

b. By applying the load through a spring.

91. a. Not always; the load may be redistributed among other members.

b. The link in the chain cannot get relief by yielding, since the entire load continues to act through it and the chain will fail. One strand of wire in a cable can "get out from under" by stretching slightly to permit other wires to be more highly stressed (if they can take it).

c. The link in the chain corresponds to the situation of Question 90. The wire resembles the condition of the test, since the load carried by the wire was automatically reduced as the specimen yielded. Only as added movement of the testing head of the machine occurred was it possible to follow up a yielding in the specimen.

d. Both conditions are plentiful with respect to machines and structures. Elements which are statically determinate will fail when their ultimate strength is reached, but a statically indeterminate structure has redundant or excess elements which may be able to assist when other elements are overloaded. Such a re-allocation of stresses is called *redistribution*. Ductility in a bar permits such a redistribution of stresses over the cross section of the bar where a local overstress occurs.

92. a. It is probably due to a strain lag somewhat analogous to the phenomenon of hysteresis. In testing at usual rates, the material does not immediately adjust itself fully to the load. Until impact conditions are approached, the more rapidly the load is applied, the higher will be the stress at the first or upper yield point. For very slow application of load the upper and lower yield points tend to coincide.

b. The lower yield point, for reasons apparent from the discussion of part a.

c. The upper yield point, especially on the beam type of weighing system. On self-indicating weighing systems the two can be evaluated with about equal ease. The upper yield point corresponds to the much-used "drop-of-beam" determination.

d. The manufacturer should naturally prefer the upper yield point if his steel tends to be low in yield-point strength. Specifications place no upper limit upon yield point; they do have a lower limit.

¹ An explanation must take into account the fact that a ductile material fails in shear, whereas a brittle material fails in tension, and also the application of the theories of failure to the complex biaxial stress situation near the grips.

Problem 5

(See p. 46 for questions.)

Tensile Test of Metal in Elastic Range

93. a. See text Chap. II, Arts. 28a and 28c.
b. No (see Chap. II, Art. 28a).
94. a. Chapter II, Art. 28d.
b. Much more definite for the reasons covered under part a.
c. Johnson's apparent elastic limit.
95. a. Chapter II, Arts. 28b and 28e.
b. Yield strength. Yield strength, as a measure of elastic strength, can be applied to all structural materials. Only ductile metals, such as medium and low-carbon steels, have yield points.
c. Spring steel has no yield point.
d. Yes.
96. a. A mild steel bar that has been previously stressed above its yield point may be expected to show a yield point about equal to the highest stress previously attained and a much less pronounced yielding than at the first test. Its ultimate strength will be approximately equal to that of the original bar, and its ductility will be decreased. Of course, in the previous partial test the bar secured a substantial portion of its ductile elongation. The total permanent elongation from both tests will equal or exceed that from a single test carried through to failure. Values for the other measures of elastic strength, as well as the yield point, the elasticity, and the modulus of resilience will be increased. The modulus of toughness will be decreased, and the modulus of elasticity will be practically unchanged (slightly lowered).
b. Successive loadings below the proportional limit have little effect upon any of the properties of a steel bar unless there be many thousands of repetitions, under which circumstances the bar may fail by progressive fracture, commonly known as fatigue.
c. Because successively increasing portions of the initial capacity of the nonoverstressed bar to deform have been exhausted. For a bar broken after a series of increasing applications of over-stress, the summation of all the successive ductile deformations may be expected not to differ greatly from the total ductile deformation that the bar would have shown at a single test to failure. This fact seems to be sufficient to account for the apparent lack of ductility characteristic of cold-worked or overstrained material.
d. Because the grains or crystals are free to readjust themselves with respect to the surrounding grains and are, therefore, incapable of assuming a condition of strain. Hot-working does refine the structure by breaking down and realigning crystals, but the strains are imposed without accompanying residual stresses.
e. For the reason given under 96d. At the critical temperature the crystals acquire sufficient mobility to reform under the stresses that accompany over-strain, thereby relieving themselves and reducing the stresses to zero.
- f. Tensile or compressive overstrain approximates that condition. Cold-twisting affects virtually the whole cross section, as does cold-drawing, but in both cases the outer portion receives the more severe overstrain. Cold-rolling affects the outer portion to various depths, depending upon the severity of the treatment. Thus, while the general nature of cold-working, of whatever sort, is simply overstrain, different types of cold-working may be expected to produce somewhat different effects on properties and on the behavior of the material under service or test.
97. See Chap. II.
98. See Chap. II.
99. a. No. Soft rubber may have an elasticity as much as 1000 times that of a steel which has a modulus of elasticity 300,000 times that of rubber.
b. 28,000,000 to 31,000,000 p.s.i. 30,000,000 p.s.i. is a convenient and widely used value. For the softer grades of steel, intermediate, structural, etc., 29,000,000 p.s.i. is probably a better average value than is 30,000,000 p.s.i.
c. Stainless steels and high-nickel steels have moduli of elasticity of about 26,000,000 p.s.i.
100. a. Measurements of lateral strain.
b. No units; a ratio (see Chap. II).
c. Yes. Poisson's ratio is one of the elastic constants of a material. Values for its nonelastic equivalent can be determined for stresses beyond the proportional limits but this nonelastic equivalent of Poisson's ratio increases as the stresses increase above the proportional limit.
d. 0.25 to 0.30.
e. Aluminum, copper, and nickel have Poisson's ratios of about 0.33; for concrete, values as low as 0.10 and as high as 0.25 have been recorded, but extensive recent tests over a great variety of mixtures indicate that it rarely falls outside the range of 0.16 to 0.23 with 0.20 probably a convenient and reliable mean value.
101. a. The strain will be greater for a given stress when the increment method is used since the specimen continues to deform to some extent with an accompanying reduction in load during the delay incident to balancing the machine and reading the instruments.
b. Insignificant in early stages of test, but important in later stages where stress is high and specimen is deforming rapidly.
c. Owing to release of load from continued elongation of specimen at constant or slightly diminished stress. The increase of strain under sustained loading is called *creep*. It has also been termed *plastic flow* or *flow under sustained load*. These terms generally apply to loads held on for considerable periods, as days, months, or years. Unless the stress is quite low, the phenomenon of creep is measurably present for most materials during a relatively short-time loading. In fact,

the rate of creep is often greatest just after the load is applied.

102. a. Stressing the material above its proportional limit, especially to or above its yield point.
 b. The presence of unannealed material that has been stressed to or above its yield point.
 c. Cold-working.
 d. Cold-rolled shafting, cold-drawn wire, cold-twisted bars.

Chapter V

(See p. 51 for questions.)

Compressive Tests

103. a. Compressive specimens are generally less slender than tensile specimens and usually have a greater area of cross section.
 b. In general, a testing machine of greater load capacity is required for compressive tests of material of a given strength than for tensile tests.
 c. Any lack of straightness, homogeneity, and initial alignment introduce eccentricity of resistance. In general, eccentricity tends to decrease as a tensile test progresses, but in a compressive test the eccentricity becomes greater because of added bending. These are, therefore, important items.
 d. The requirements for a proper transfer of load are usually more exacting and more difficult to meet adequately in a compressive test than in a tensile test.
104. a, b, c, and d. See text.
105. a. Yes. Vitally important at all stages of loading because good knife-edges do not freeze and the crossed knife-edges permit tilting adjustments to occur in any direction throughout all stages of the test. Obviously, such tilting strains the specimen unequally.
 b. Yes. Eccentricity will be present by whatever amount the axis of load misses the axis of resistance (presumably the geometric axis of the specimen). The axis of the load ceases to be determined by the centroid of the block as soon as friction forces develop over the spherical surface to such an extent that the capacity of the block to adjust itself is exceeded. The more imperfect the centering, the greater is the load required to "freeze the block," because the eccentric bending moment that produces movement of the block is correspondingly greater. Careful, accurate centering needs to be recognized as a necessity whenever a spherical bearing block is used.
 c. No. The case resembles that of the frozen block.
106. a. Decrease it.
 b. More load.
 c. The bending effects from eccentricity will be less severe at the most stressed portions of the cross section than for the unrestrained crossed knife-edges, as is explained in the discussion of the previous question.
107. a. Derive from basic expression $S = \frac{P}{A} \pm \frac{Mc}{I}$ (see chapter on direct stress and bending or on eccentric loading in a text on mechanics of materials).
 b. On the face nearer the load.
 c. Zero.
 d. One-half.
 e. For the same load there would be still compression on the side of the load and greater tension on the opposite face. Less load would be required to produce a given maximum stress.
 f. Yes.
 g. No. The expression for the bending stress ($S = Mc/I$) is valid only for stresses within the proportional range, and computed values will be only approximately correct.
 h. Results from tests to the ultimate should show a total load more than half of that for the well-centered load; the effect of the overstress being to offset the effect of eccentricity partially through redistribution.
108. One-eighth the diameter. To avoid tension over any part of the cross section, the load would need to be kept within the middle fourth of any diameter.
109. a. No.
 b. Grind the end to a plane surface, or cap it with plaster of paris or some other quick-hardening plastic.¹
 c. No. Often employed as a makeshift method and may give fairly good results in many cases.
 d. See text.
110. a. In general, such errors are cumulative in their weakening effect.
 b. They decrease the load the specimen can carry and make the material appear to be weaker than the standard procedure would indicate.
111. No. Practical conditions have almost infinite possibilities for variations of indeterminate amounts. To the known constants determined under idealized conditions, one can apply such factors of safety as seem to be warranted in the light of judgment and current specifications or regulations under which the design is being prepared. Efforts to "make tests practical" generally produce results that are valueless because of inability to appraise them in comparison with either practice or standard tests.
112. a. No. The load enters the post through the pin.
 b. Probably some eccentricity since the centroid of the bearing is doubtless between the inner edge and the centroid of the post.
 c. By frame analysis it can be shown that with a rigid connection to a relatively stiff post the eccentricity approximates one-fourth of the span of the beam.
113. No. See text. Use of two spherical blocks may be dangerous because it promotes instability of setup. Where large forces are applied, precautions against specimens flying out of the machine or any other sudden release of load are important.

¹ Some of the most recent data on the effects of capping concrete specimens are reported in the following paper: Troxell, G. E., The Effect of Capping Methods and End Conditions upon the Compressive Strength of Concrete Test Cylinders, *Proc. A.S.T.M.*, Vol. 41, 1941.

114. *a.* The factors are empirical. They simply represent approximations from tests of concrete specimens.

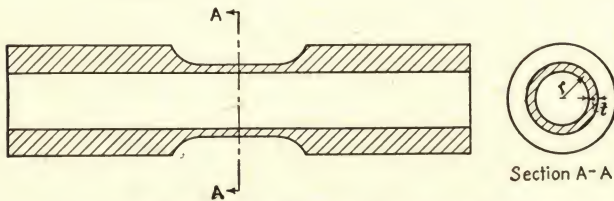


FIG. 31.—Specimen for evaluation of torsional properties for stresses which exceed the shearing proportional limit. (See answer to Question 124.)

- b.* They should apply reasonably well to similar specimens of other materials. The deviations might well be considerable for material which was either much more brittle or much more ductile than concrete because of possible differences in the effects of secondary stresses above the proportional range.
115. *a.* Column action (bending effects from length of member) does not begin to be very apparent until the h/d ratio approaches 15 to 20, but there is nevertheless a slight lowering of the yield strength as the length increases above an h/d ratio of 2. None of the specimens listed is seriously over length therefore, but several of them are somewhat longer than is generally considered best from the standpoint of test for strength only.
- b.* Apparently for practical reasons several of the specimens have less than the desired h/d ratio of 2 (see Art. 48 for discussion of these factors).
116. No. From the ratios of Art. 48, the compressive strengths of the two materials should be about the same (see text).

Problem 6

(See p. 53 for questions.)

Compressive Test

117. See Art. 39 and data of the test.
118. Small clear specimen. A full-size member of timber contains various minor, if not major, defects, all of which reduce the average strength that a test would develop.
119. The center of resistance at that section would not coincide with the geometric axis of the specimen, which is the center of resistance for homogeneous sections. Thus the knot introduces the equivalent of eccentricity.
120. *a.* Numbers 1, 2, 5, 6, 7.
b. Numbers 1, 2, 3.
121. Yes. For materials such as timber, portland-cement mortar, and concrete the properties are definitely affected by the moisture content.

Chapter VI

(See p. 55 for questions.)

Shearing and Torsional Tests

122. *a.* Parallel paths across the section in cross shear and circular paths in torsional shear.

- b.* In cross shear the maximum shearing stress occurs along the neutral axis of the cross section, and the shearing stress is zero at the extreme fibers (see horizontal shear in beams in textbook on mechanics of materials). Under torsional shear on a circular cross section the maximum shearing stress occurs at the periphery of the cross section, and the stress is zero at the center (see torsion in textbook on mechanics of materials).

c. See Art. 54.

123. The ductile material fails in shear along a plane of maximum shearing stress, which is normal to the axis of the specimen. The brittle material, instead of failing in shear, fails by diagonal tension, which is a maximum at angles of 45 deg. with the shearing stresses. This diagonal failure occurs with materials which are weaker in tension than they are in shear.

124. *a.* In a circular bar, torsional strain varies directly with the distance from the centroid, and within the proportional limit stresses will also vary directly with the distance from the centroid. The formula for torsional stress is derived on the basis of this relationship and ceases to give correct results when the stress ceases to be proportional to the distance from the centroid of the section.

- b.* All the material in the thin-walled cross section is concentrated at nearly the same distance from the center and is under practically uniform stress. If t is small, S is practically uniform over the area $2\pi rt$ and is approximately correct within any range of stress.

125. *a.* Too high. As soon as the stress in the material at the surface of the bar exceeds the proportional limit, the formula for torsional stress ceases to be valid. Evidence of yield point is not discernible until after material some distance inward from the surface has been overstressed and the "fictitious stress," given by the formula $S = Tc/J$, exceeds the stress actually present at the surface of the bar.

- b.* The explanation above applies to modulus of rupture in a greater degree than it does to the yield point, for similar reasons.

126. *a.* No. The strain is not proportional to the distance from the centroid of the bar, as it is for a bar of circular section, and a plane cross section before stressing is not plane under stress. The torsional stress analysis of bars of noncircular cross section falls somewhat beyond the usual undergraduate course in mechanics of materials.

- b.* The square bar is only about 6 per cent stronger, although its area is 27 per cent greater than that of the round bar. The extra area does contribute something to the resistance offered.

- c.* The round bar, since the material in the vicinity of the corners of a square bar contributes little to its torsional resistance. A torsional analysis of a square bar shows the stress at the corners to be zero.

127. From the standpoint of the effectiveness of a torque-transmitting member the shaft may be made hollow to save weight. Pound for pound the core material con-

tributes relatively little to the torsional resistance of a shaft. Every ton of weight saved is potentially an added ton available for pay load. In specific cases, other considerations such as machining costs, vibration effects, impact resistance, and the general proportioning of the masses might well become dominant.

128. No. A shearing stress is always accompanied by an equal shearing stress on a plane at right angles to it (see a textbook on mechanics of materials).

129. No. A brittle material will fail in tension before it will fail in shear.

Problem 7

(See p. 56 for questions.)

Shearing Test of Rivet Steel

130. No. Bending of the specimen and local crushing of the specimen and the plates would be registered as shearing deformation.

131. a. Answer in the light of your data.

b. Under double-shear conditions the testing setup is a symmetrical one and in single shear it is not, with the result that there is a greater tendency for bending and direct tension in single shear. However, such differences as exist seem to be almost, if not entirely, negligible in their effect on the unit-shearing resistances for the two types of test.

c. No. These tests are too few to indicate more than a possible trend. Consistent results would have to be secured from a great many more tests than these to warrant any generalization on the subject.

132. Bearing and bending. Rather more bending in single shear than in double shear.

133. No. Other types of possible failure are crushing of the rivet against the plates (and failure of the plates themselves by tension on net sections), diagonal tension between rivet holes of adjacent rows, or shearing between rivet holes and adjacent edges of plates.

134. a. A.S.T.M. Designation A141-39 for Structural Rivet Steel specifies tests for tensile strength, tensile yield point, elongation in 8 in. and a cold-bend test. All these tests are performed on the bar stock rather than on rivets. A.S.T.M. Designation A31-40 for Boiler Rivet Steel and Rivets specifies the above tests on the bar stock and an additional quench-bend test. The second portion of A31-40 lists a cold-bend test and a hot-head-flattening test to be performed on rivets.

b. No. Apparently the subcommittees of Committee A-1 which formulated these specifications, were satisfied (on the basis of tests, experience, and/or judgment) that the safety of rivets against failure in shear was insured by the chemical composition and physical tests which are required.

135. There are, of course, many differences. A few of the more apparent may be mentioned. Under service conditions rivets are driven at red heat and should be under some initial tension after they have cooled. This produces considerable frictional resistance between the connected surfaces and under the heads of the rivets. This friction

will probably be overcome in service, but, when moderate loads are first applied to riveted joints, most of the resistance developed is frictional rather than shearing. In other words, there must be some slippage or yielding of a riveted joint before it can begin to function as a riveted joint is designed to function.

136. No. Except for surface oxidation a steel as low in carbon as rivet steel is practically unaffected by heating and cooling. If anything, the vigorous hot-working which the rivet gets while being driven may refine the steel of the rivet an additional amount, tending to make it somewhat superior to the rivet stock. The difference cannot be very important, however, as the bar stock was thoroughly hot-worked during rolling.

137. a. Yes. Theoretically there is no limit to the shearing resistance that can be developed by multiplying the rivet areas.

b. Yes. Condition similar to the preceding case.

c. No. Efficiency in tension can be made to approach but can never be made to equal 100 per cent.

138. See Art. 54.

139. a. Maximum intensity of cross-shearing stress in a circular cross section is $\frac{4}{3}$ of the average stress.

b. At the neutral axis of the cross section (see chapter on horizontal shear or shear in beams in a textbook on mechanics of materials).

Problem 8

(See p. 57 for questions.)

Torsional Test of Steel

140. No. In a torsional test of ductile steel the bar twists in two without the necking down or reduction of area which characterizes a tensile test of similar steel. There is not, therefore, the considerable decrease of load carried due to a decreased area of resistance.

141. For $E = 30,000,000$ p.s.i. and $m = 0.25$, $E_s = 12,000,000$ p.s.i.

142. Ordinarily the modulus of resilience in shear is the most important because it represents the capacity of the material to store and to release energy elastically; to withstand elastic shock. If, however, there are to be a great many repeated applications of load, the torsional endurance limit may be of equal or greater importance than a high modulus.

143. a. Torsional shear; can be free of bending.

b. Torsional shear because the shearing deformations can be produced and measured accurately over any desired gage length.

c. Torsional shear for each of the properties listed under Item *E*. Reasons are apparent from parts *a* and *b* and from Art. 54.

144. a. The maximum stress of $\frac{4}{3}$ the average occurs at the neutral axis of the cross section (a diameter normal to the plane of bending).

b. Zero at the surfaces of the bar farthest from the axis of bending.

c. (1) Shearing stress is assumed to be distributed uniformly over the cross section, the factor of safety being depended upon to allow for the fact that the maximum stress in the cross

section exceeds the average. The stress situation in a rivet is complicated at best and no attempt at an accurate rational analysis is warranted.

- (2) By computing the intensity of the maximum shearing stresses and designing to keep these below the maximum shearing stress permitted in the specification. The stress situation in the beam is susceptible of rather accurate analysis.

145. No, since only the surface of the bar is stressed to its proportional limit.

146. a. No. At the ultimate load only the outside material was stressed to its ultimate. When failure came, it started at the outside and traveled inward.

- b. No. Up to, and including, the proportional limit, stress calculations are valid. Above the proportional limit, stress calculations are not valid, the error increasing as the maximum stress increases.

Problem 9

(See p. 59 for questions.)

Test of Helical Spring

147. Modulus of rigidity (pounds per square inch); modulus of the spring (pounds). These two properties can be evaluated from observations within any convenient portion of the proportional range of stress. Two of the other properties listed (*b* and *c*) would necessitate observations up to the proportional limit and the other one (*d*) would require a test to failure.

148. a. Ratio of stored energy in tension to that in torsion; $\frac{S^2}{2E} \div \frac{S^2}{4E_s} = \frac{4E_s}{2E} = \frac{(4)(12)}{(2)(30)} = \frac{4}{5}$ or 0.8. At

identical maximum stresses the tensile bar can store only 0.8 as much energy as the bar under torsional stress, even though all the material in the tensile bar is stressed to the limit and in the torsional bar only the surface material reaches that stress.

- b. Ratio of stored energy at the proportional limit is $\frac{S^2}{2E} \div \frac{(0.6S)^2}{4E_s} = \frac{S^2}{(2)(30)} \times \frac{(4)(12)}{0.36S^2} = \frac{24}{10.8} = 2.22$

While the lower modulus of elasticity in shear (modulus of rigidity) gives torsion a considerable advantage over tension, the lower proportional limit in shear together with the variation in the stress distribution leaves the net advantage considerably on the side of tension for the actual maximum value for modulus of resilience.

149. No. In flexure the stress varies over the cross section much as it does in torsion and not all the material can be stressed to the permissible limit. The average energy per cubic inch of material that can be stored in a simply supported rectangular beam under a concentrated load at mid-span is $\frac{1}{18}S^2/E$. The ratio of the limiting stored elastic energy per unit volume of the rectangular steel beam to the energy per unit volume of a torsional

member of circular cross section is $\frac{1}{18} \frac{S^2}{(30)} \div \frac{1}{4} \frac{(0.6S)^2}{12} = \frac{1}{4.05}$. Thus it is apparent that for steel, torsional energy storage

has an advantage of nearly four to one (see preceding discussion) over straight flexural energy storage. Leaf springs having a variable cross section are widely used for flexural energy storage. These reduce materially the differential in energy storage capacity between torsion and flexure.

150. The available range of deformation is too limited; there is no cushioning of the load, which is itself relatively very high.

151. a. The external energy (the work) performed on the spring could be equated to the energy absorbed torsionally plus the energy absorbed by the cross-shearing stresses plus the energy absorbed in bending and in direct compression.¹ These internal energies could be summarized by use of the calculus. A fair approximation for this purpose may be had by assuming the cross-shearing stress to be distributed uniformly over the sections dealing with average cross-shearing stresses instead of summarized variable values.

b. Torsional stress greatest at outside surfaces; cross-shearing stress greatest at neutral surface for bending.

c. Yes. They may be added algebraically at all points since they lie in the same plane and are in the same direction. The greatest stress (the sum of the two) on any cross section occurs at one of the intersections of the neutral axis with the surface. Here both attain maximum values.

152. Higher values would have been obtained. If all other factors are the same, the less the deformation under a given torque, the stiffer is the material. The deflection measured included some shortening due to bending, cross shear, and direct compression and to this extent the value for the modulus of rigidity is in error on the low side.

153. a. Lower.

b. Unsafe.

c. Lower.

d. Less stiff.

e. No. The modulus of the spring is a function of deformation and load and is independent of the mechanics of the deformation.

f. No. The energy stored is a function of the force on the spring and the displacement produced by that force. Explanation is similar to that in the preceding question for the modulus of the spring.

154. Less. The torsion formula gives values for stress which are too high when the proportional limit of the material is exceeded.

155. a. Yes.

b. Yes, so far as the total energy stored and the modulus of the entire spring were concerned, but not for such properties as (1) modulus of the spring per turn, (2) modulus of rigidity of the metal, (3) the stored energy per unit volume of metal. The distorted metal near the ends would be stressed and deformed differently from the metal in the portion with uniform cross section, and the differences would be averaged in to

¹ The compression is obviously very small in most cases, being the compressive component of the load due to the inclination of the coils.

produce incorrect results for the three properties listed above.

156. No. Slight variations in the diameter of the helix have only a small influence upon the values for the calculated results, but the same is not true as regards the diameter of the bar. Most of the computed properties involve either the cube or the fourth power of the diameter of the bar, but only the first power of the diameter of the helix.

157. $e = \frac{c}{R} \Delta$ in which e = total strain in the outside fibers, c = radius of the rod, R = mean radius of the helix, and Δ = deflection of the spring.

158. Use data from your test. A similar case may be assumed for a spring with a mean diameter of 5 in. and a coil spacing of 1 in. In the illustrative case the inclined length of one turn exceeds the horizontal length by a difference less than either the measurements or the slide-rule calculations can justify as being significant.

159. No. The formulas used are applicable only to circular cross sections (solid or hollow with uniform thickness of wall).

160. a. By applying the load to the specimen through a previously calibrated spring, the load being measured by observations of spring deflection on three gage lines 120 deg. apart around the spring. These measurements may be made with ruler or scale, with or without the aid of dividers, with a strain gage, or by means of Federal or Ames dial indicators attached to the gage lines. Such a rig can be devised with almost equal ease for tensile and compressive testing, the tensile arrangement generally being somewhat the more elaborate of the two.
- b. Place the assembly in the testing machine, apply the desired load, and tighten the nuts on the ends of the rods until the load on the testing machine is fully released but no more. The specimen has then been loaded. Reverse the process at unloading by applying load to the testing machine until the nuts are just free to turn. The beam of the machine is read. If the load is in close agreement with that at loading, there will have been no measurable release of load by deformation (plastic flow or creep) in the specimen, the spring, or the testing cage. If there has been some release it is a matter of judgment to decide whether or not the average load should be considered to have been a mean of the measured initial and final values.
- c. The spring can be used as both the load-applying and load-measuring device by tightening the bolts to produce any desired deflection in the spring as measured by one of the methods mentioned in part a. During the test, load may be added or released by following the same procedure.
- d. Modulus of the spring is 10,000 lb. A deflection of 0.03 in. for a 10,000-lb. spring represents 300 lb. of load leaving the load on the specimen 4700 lb. at the end of the loading period. This is a reduction of 6 per cent of the initial load. The same result may be obtained by using the deflection as 0.03 is 6 per cent of 0.50.

161. a. By interposing (with proper safeguards) a spring between the specimen and the testing machine. With a spring in series with the specimen, the

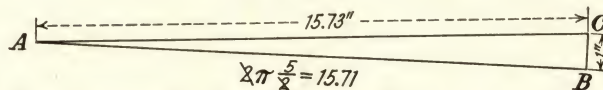


FIG. 32.—Very slight effect of inclination of spiral on length of bar. (See answer to Question 158.)

specimen can, as it yields, "get out from under" the load to only a very limited extent. Thus the introduction of the spring simulates the condition of a load free to follow down and cause collapse of the specimen when and if its ultimate resistance is passed.

- b. In attempting to hold a sustained load on a specimen in any of the usual types of testing machines, the load is substantially reduced when the specimen yields even slightly. Minor yielding becomes relatively unimportant in its effect on load if a spring is introduced (with proper safeguards) between the specimen and the testing machine. In this manner a specimen can be kept in a testing machine under an almost constant load for as long as is desired, especially if at convenient intervals the head of the machine be moved to restore the full initial deflection to the spring.

Chapter VII

(See p. 62 for questions.)

Flexural Tests

162. No (see Chap. II, Art. 29).
163. a. Strength (of whatever kind).
b. Elasticity and ductility.
c. Stiffness, resilience, and toughness.
164. a. The slower the rate of application of a given static load the greater will be the deflection corresponding to the load.
- b. More pronounced. The increased deflection is due to creep or plastic flow, and, for the materials which behave elastically, these effects are likely to be quite indiscernible until the stresses are above the proportional limit. From this point on, the higher the stress, the greater will be the creep effect during a given interval of time.
- c. No. Probably in no case can a beam support its maximum load indefinitely, although materials differ greatly in the time that would be required for a load just below the maximum to produce collapse.
- d. No. It will increase, although again there is great variation in the amount and the rate of increase for different materials. For steel at ordinary temperatures the increase would be very slight and difficult to detect. (Both the yield point and the proportional limit of steel are invariably more than 50 per cent of its ultimate strength even for the softer grades.)

Such materials as timber and concrete (both plain and reinforced) take on relatively large added deflections under sustained loads which are even less than half their ultimates.

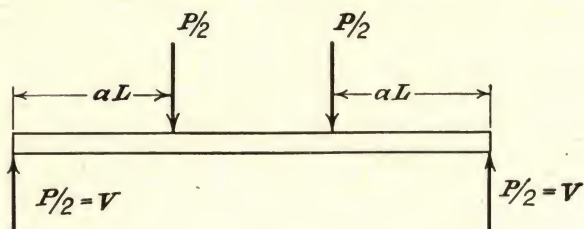


FIG. 33.

165. a. A beam may fail by compression or tension in the extreme fibers at the section of maximum bending moment, or by horizontal or vertical shear or by diagonal compression or diagonal tension in a region of high shear.
 b. The primary failure is the initial breakdown. A secondary failure is a follow-up of the primary failure, having been brought about by it.
 c. No. Oftentimes the primary failure is inconspicuous, and the secondary failure is spectacular. Timber, for example, is usually somewhat weaker in compression than in tension, and the primary failure in flexure is likely to be a slight and imperceptible buckling of compressive fibers. After these yield somewhat, the tensile fibers are torn apart and the fractured specimen shows every evidence of having failed in tension, which was after all a secondary phenomenon, brought about at that stage by readjustments contingent upon the buckling of the compressive fibers. The difficulties in identifying the primary cause of failure by examining a tested specimen are more or less analogous to those encountered in trying to tell what started a fire by examining the ruins, or by trying to determine which member of a collapsed building gave way first.
166. Below the ultimate load the work expended upon a specimen is well distributed; practically the whole specimen is working. At the ultimate load the resistance of some portion of the specimen decreases, and from that stage on the work is localized largely in the region of impending failure. (The necking down of a ductile tensile specimen illustrates the local concentration of energy for that type of test.) The toughness at the ultimate is much the more significant and useful criterion, but the toughness at rupture is the larger (often much the larger) quantity. This is shown by the area added below the stress-strain or load-deflection curve in the last stages of the test. For a brittle material, rupture occurs at or near the ultimate, and the work at ultimate and that at rupture may be identical or nearly so (see Question 89, Prob. 4).
167. a. Strength and stiffness both doubled.
 b. Four times as strong; eight times as stiff.
 c. Half as strong; one-eighth as stiff.
 d. Strength unchanged; stiffness doubled.
168. No. E , the measure of stiffness, does not appear in the flexural formula by which strength is evaluated.
169. The remaining word should be
 a. Inversely.
 b. Inversely.
 c. Directly as L^3 .
 d. Inversely.
 e. Does not vary.
 f. Directly.
170. Decrease it, because the added restraint or lack of adjustability stiffens the setup.
171. a. They minimize any tendency of the beam to be twisted because of failure to bear uniformly over the width of the support or to have the load bear uniformly across the beam.
 b. No. The adjustment under the load and at one end provides all that is necessary to avoid twisting. The added flexibility of rockers at both ends accomplishes no needed function and tends to make the setup unstable, which is always to be avoided.
172. a. The reaction is $\frac{1}{2}P$, and the load reading is P .
 b. The reaction is $\frac{2}{3}P$, and the load reading is $\frac{1}{3}P$.
 c. The reaction is $\frac{1}{3}P$, and the load reading is $\frac{2}{3}P$.
173. a. By referring to A.S.T.M. Designation A48-41, Sec. 5, one may observe that the different diameters are to serve as the controls for sections of different thickness in the castings which they represent. (In gray iron castings the thickness of the sections has much to do with the final quality of the metal because of the effect of different rates of cooling on the structure of the iron and also because of shrinkage stress concentrations especially at junctions.)
 b. The longer spans are for the larger bars, and, while the ratio of span to diameter is not constant, the longer spans tend to make the relative proportions of the specimens reasonably similar. The longer span also serves to reduce the load that can be carried at mid-span on the larger bars, thereby permitting the use of a testing machine of lower capacity.
174. a. $M_{\max.} = aL \frac{P}{2} = S_r \frac{I}{c}; \frac{P}{2} = \frac{1}{aL} S_r \frac{I}{c} = \frac{1}{aL} S_r \frac{bd^2}{6};$
 but $S_s = \frac{3V}{2bd}$ (for a rectangular cross section) or $V = \frac{P}{2} = \frac{2}{3} S_s bd$. The $V = \frac{P}{2}$ must be the same for both conditions if the beam is to be equally resistant to failure from moment and from shear. Then $\frac{1}{aL} S_r \frac{bd^2}{6} = \frac{2}{3} S_s bd$, from which $aL = \frac{d}{4} \frac{S_r}{S_s}$.
 b. If one refers to Fig. 33, it is apparent that when $a = 0.5$, $aL = 0.5L$. The loads are both at mid-span, and the distance between them is zero. For all values of a below 0.5 the distance between the loads for any fixed value of aL has no effect on the magnitude of either the shear or the moment and presumably has no influence on the resistance which the beam can offer.
 c. For a concentrated load at the center $aL = 0.5L$ and $L = \frac{d}{2} \frac{S_r}{S_s}$.
 d. Because S_r is the modulus of rupture, a fictitious ultimate fiber stress in bending, and S_s represents

the ultimate shearing resistance. The formulas in which these are used are invalid above the proportional limit of the material in bending and shear, respectively.

175. a. The tensile strength should be used since the beam fails in tension. The diagonal tension and diagonal compression are both numerically equal to the shearing stress present on horizontal and vertical planes.
- b. $aL = \frac{d S_r}{4 S_s} = \frac{d 800}{4 400} = \frac{d}{2}$. Since the standard beam (Art. 51) is 6 in. in cross section, aL must equal or exceed 3 in. The 18-in. span with loads at the third-points should, therefore, be ample to insure bending rather than shearing (diagonal tension) failures.
- c. $aL = \frac{d 10,000}{4 500} = 5d$. For a depth exceeding 12 in., a beam of this timber in structural sizes on a span of 15 ft. (Art. 57) would probably fail by horizontal shear instead of bending.
- d. $aL = \frac{d S_r}{6 S_s} = \frac{d 40,000}{6 20,000} = \frac{d}{3}$. There is evidently not much probability of getting diagonal tension failures in flexural specimens of this grade of cast iron.

Problem 10

(See p. 64 for questions.)

Flexural Test of Timber

176. The modulus of rupture should be considerably higher for the small clear specimen because of its relative freedom from defects. The modulus of elasticity also should be somewhat higher although the effect of such defects as might be expected in a good full-size member might be less evident within the elastic range of stress than in the vicinity of the ultimate load.

177. a. Both properties decidedly lower for the saturated specimen.
- b. The maximum effect on properties is reached in timber when fiber saturation is attained. A waterlogged, or thoroughly soaked, piece of wood may contain considerable free water over that required for fiber saturation, and this excess water has little if any added effect on the properties which are evaluated by test.
178. For short spans or for loads placed near the supports, the shearing resistance of the beam will determine the load it can carry. As the loads are placed farther from the supports, as is always the case for central loads on long spans, bending moments increase and the fiber strength will determine the load the beam can carry. A load P at the center of a span produces a shear at each end of $V = P/2$ regardless of the span; it produces a bending moment at the center which increases as the span increases. Thus, in general, shear may be expected to control the loading in the case of short spans and moment in the case of longer spans.
179. a. The indentations under the load and at the supports would have been measured as deflections, and all properties dependent upon the magnitudes

of deflections would have been influenced thereby. The modulus of elasticity would have been decreased because of apparent added flexibility.

Values of the resilience of the specimen, the modulus of resilience of the material, the total work to the ultimate, and the average energy at the ultimate will all be increased because the added apparent deflection increases the areas under the load-deflection diagram.

- b. The answer will depend on the setup used (see Questions 194 and 195, Prob. 11).
180. a. Timber is usually stronger in tension than in compression.
- b. Examine the evidence.
181. a. The elastic deflection Δ at mid-span from bending is $\Delta = PL^3/48EI$, where P = load, L = span in inches, E = modulus of elasticity in bending, I = moment of inertia of cross section with respect to axis of bending. Assuming average shearing stress over each cross section

$$\Delta_s = \epsilon_s \frac{L}{2} = \frac{S_s L}{E_s 2} = \frac{V L}{bd 2E_s} = \frac{P L}{4bd E_s}$$

$$\Delta_s \div \Delta = \frac{d^2 E}{L^2 E_s}$$

For this beam

$$\Delta_s \div \Delta = \frac{4 E}{(28)^2 E_s} = \frac{1 E}{196 E_s}$$

Obviously the shearing deformation is so small that it is lost among the other uncertainties and inaccuracies of the test.

- b. Negligibly smaller.
182. a. Within the proportional limit the moduli of elasticity of any material in tension and compression are theoretically equal. It follows that the flexural modulus should be the same as these, since it depends solely upon them.
- b. If the two moduli do differ somewhat, the flexural modulus should have a value between the other two.
183. In comparison with other structural materials timber is relatively resilient, tough, strong for its weight, and elastic. It has good capacity for nonelastic deformation but cannot be termed ductile. Relatively, it is neither brittle nor stiff. Between different woods and also between different states of dryness, all the above properties fluctuate considerably, but the general statement above is reasonably correct for all structural woods.
184. Since the maximum unit stress is beyond the proportional limit in shear, the formula used for its calculation is not valid, and the results are, therefore, approximate.

Problem 11

(See p. 65 for questions.)

Elastic Curve of a Beam

185. a. They are one-third as large. Within the proportional limit, deflections are directly proportional to load.

- b. Most of the experimental errors, such as the inaccuracies in reading dials, are more or less fixed. About the same total error was present in each one-third load reading as for the full-load readings. The maximum full-load deflection should have inherently the lowest percentage of observational error, and it is, therefore, the logical choice as the basis for determining the value of E .

186. At the dial which indicated the greatest deflection. The value of E used as the basis for deflection computations was determined from the measured deflection at this point. Agreement of deflections at this point simply closes a mathematical circuit.

187. A difference between the assumed value and the true value of E for the beam and differences between the actual behavior of the beam and its theoretical behavior as defined by the computed deflections. If differences were due to differences in E , the two curves would not coincide but would be approximately parallel. Differences due to fundamental differences in behavior would produce curves of different shape which might even cross one another.

188. The diagram represents a smooth averaging of all observations at a given load point and should give more reasonable values than could be expected from any one observation.

189. a. No. They were present when the zero-load readings were taken.

b. No, for the same reason as above.

190. a. Between the load and mid-span.

b. For the load at mid-span.

191. Deflections would be too small.

192. a. Greater.

b. No. The deflection formulas would no longer apply.

193. No. Among the limitations imposed on the formulas used in the theory of flexure is that "the plane of the loads be a plane of symmetry of each cross section." Lack of symmetry of member or of load produces twisting, and the computed deflections will not agree with those observed.

194. No. Any deflection of the bed of the machine or deflection of the supports would have been registered as deflection. For some situations these errors might not be great, but for others they might be considerable. All sources of more or less indeterminate errors that might be appreciable need always to be avoided scrupulously in deciding upon alternative techniques of testing.

195. a. If the reference bar was attached to the beam itself, no error was introduced by the local crushing.

b. Yes. All local crushing at the supports and under the load would have been measured as deflection.

196. a. The deflection due to moment will be relatively much smaller on the short span, because the deflection due to bending varies as the cube of the span whereas the deflection due to shear varies as the first power of the span.

b. Yes.

c. In some cases it might be necessary or desirable to take account of shear deflection. As pointed out in the discussion of Question 181 (under

Prob. 10), the effect of shear is relatively very slight.

d. Determine from the data, assuming the shearing stress to be distributed uniformly over the cross section.

197. a. As ordinarily derived, the equation for the elastic curve of a beam is referred to the left reaction as the origin. In this case it is much simpler to compute deflections between the left reaction and the load than it is beyond the load. The answer for the usual situation is, therefore, no.

b. The maximum deflection lies between the load and the mid-span, and it is obvious that the point of maximum deflection lies beyond the load. The simplest thing to do is to "walk around the beam," figuratively speaking, in which case the maximum deflection will lie within the left three-quarters instead of the right three-quarters of the span.

198. a. There is a vertical displacement in the shear diagram.

b. The moment diagram changes direction abruptly (two adjacent moment curves meet at an angle).

c. Two different elastic curves join with a common tangent.

d. The question is misleading. There can be no discontinuity in the curve of the deflected beam unless the fibers are kinked, which would mean overstress to the point of local failure. There will be gradual transitions and common tangents wherever there is elastic behavior.

199. a. A change in loading.

b. Point of inflection or point of contraflexure. Moment causes bending; where the moment is zero, there is instantaneously no tendency to bend and the beam is straight. As the moment changes through zero, the center of curvature shifts from one side (above or below the beam) to the other, which explains why the point is called the *point of inflection*.

c. Yes. A positive moment is one that tends to shorten the top fibers and lengthen the bottom ones, which makes the beam concave upward (tends to dish it or make it hold water). A negative moment has the opposite effect.

200. a. The shear is the sum of the loads on either side of the section. No load, no change in shear.

b. The moment equals the area under the shear diagram on either side of the section. In a region of zero shear the moment is undergoing no change.

c. In a region of zero moment the beam is unbent; the slope is constant since the curve of the beam is a straight line.

d. In a region of zero slope the beam is horizontal in which case the deflection is not changing.

The facts pointed out above form the basis for some much-used methods of structural analysis.

201. a. The power of x in the equation indicates its degree.

b. First degree: moment equation for concentrated loading.

Second degree: moment equation for uniform loading.

Third degree: elastic curve equation for concentrated loading.

Fourth degree: elastic curve equation for uniform loading.

- c. A circle (a second-degree curve). With a constant moment the bending tendency is constant, and it is apparent that the curvature should be uniform for a beam of uniform cross section. In a region of zero shear (pure bending), such as exists between the loads under two-point symmetrical loading, a flexed beam should conform to the arc of a circle.

Problem 12

(See p. 67 for questions.)

The Strain Gage

202. Refer to the plotted data.

203. a. In the precise tension test the strains were the average over the area of cross section of the specimen; in this test they were simply the strains along different gage lines on the surface of the member.

b. Stiffness (E) and other properties are determined in a tensile test; in this test stresses within the proportional limit are determined but no properties are evaluated.

c. In a tensile test E is evaluated from observed stress-strain data; in this test stresses are evaluated from the measured strain data and an assumed value of E . Thus there is a primary assumption regarding a value of a property in this test and no corresponding assumption in the tensile test, one of the objects of the tensile test being to evaluate that property.

204. a. No. The strain-gage measurement can be used to evaluate only the increment of stress due to loads added after the initial readings were taken.

b. No.

c. Strain-gage observations take no account of any stresses which were already present when the initial readings were taken, regardless of their cause.

205. Strains can be observed with a strain gage within any range of stress, but stresses can be evaluated from strains only within the range of proportionality. Large measured strains simply indicate that the proportional limit has been exceeded; the stress may still be at or below the yield point.

206. One dial division on the gage

$$= 0.0002 \div 12 = 0.0000167 \text{ for strain.}$$

One dial division on the gage

$$= (0.0000167)(3,000,000) = 50.0 \text{ p.s.i. for stress.}$$

207. a. The two-point symmetrical loading eliminated shearing effects between the loads where a state of pure bending (zero shear) existed.

b. Between the loads the strain and stress are constant along any given line parallel to the neutral surface.

208. Principal sources of error in the stress experimentally determined are as follows: errors in the gage and dial, errors introduced in manipulating the gage, incorrectness in the value assumed for E .

Principal sources of error in the values of stress as computed from beam theory are as follows: departures of cross-sectional dimensions from those assumed for calculation of section modulus, imperfect elastic behavior of the material due to lack of homogeneity or other causes, failure of the loads to lie within a plane of symmetry of the beam and any other incidental deviations from the assumptions and conditions on which the theory of flexure is predicated.

209. No (aside from possible minor variations of stress incidental to redistribution). The added deformation was from "creep" or plastic flow under sustained loading.

210. a. $L = (10)(10)(0.0000065) = 0.00065 \text{ in.}$

$$b. S = (30,000,000) \frac{0.00065}{10} = 1950 \text{ p.s.i.}$$

If tensile strains are being measured, they will be too low; if the strains are compressive, they will be too high.

$$c. S = (4,000,000) \frac{0.00065}{10} = 260 \text{ p.s.i.}$$

d. No. The error in measured total strain varies with the gage length, but the error in unit strain and unit stress is the same for all gage lengths.

e. (1) Use one gage line as a control and take repeat readings on it at intervals.

(2) In completing a series of readings take a repeat reading on the first gage line of the series.

(3) Take and record check readings on a reference bar at intervals as the work progresses.

These precautions are good for detecting any general error such as that due to a slip in adjustment of the gage or to a temperature change in the gage or the specimen. They do not provide a check against specific or individual errors such as those due to misreading the dial or to holding the gage incorrectly on a particular gage line.

211. a. The two types of gage would function alike (no temperature effects involved).

b. The use of the invar gage would be simpler. With the gage of ordinary steel, error would be present, and corrections might be needed.

c. Immaterial which gage is used. A temperature correction would be needed in either case.

d. Simpler to use the gage of material similar to that of the structure since it would be affected equally with the structure and no correction would be required. For the invar gage corrections would be needed.

e. A reference bar of invar supplies a more or less absolute reference datum, but a bar of the material under test may be the more useful for some conditions of testing. In many tests it is desirable to take occasional readings on both types of reference bar and also to record temperature readings from appropriately placed thermometers.

212. *a.* The movable leg of a Berry strain gage is the short leg of a bell-crank lever, the exact length of which is determined by the point or region of contact with the member. The larger the diameter of the hole, the farther in will the conical point extend before contact is established, and the shorter will be the length of the short leg. The error should be in direct proportion to the shortening of the short leg. If the point touches the bottom of the hole, the effective length of the lever would be increased by the distance from the ring of normal contact to the tip of the leg. The bottom contact would also lead to erratic results because the point of the gage would not always contact the same spot on the bottom of the hole at successive insertions.
- b.* No length-of-lever effect from different sizes of holes, but the erratic effect of bottom contact would be present.
213. *a.* Hold the gage in place on a gage line as the truck passes over the bridge, noting the number of divisions by which the reading varies during the passage of the truck.
- b.* Drive nails or insert metal pegs at ends of gage lines, drill gage holes in these, and take readings at intervals for a period of weeks, months, or years, depending upon the duration of the test. At every observation period readings should also be taken upon a standard reference bar.
- c.* Preliminary readings on the empty stadium, followed by readings after the crowd has gathered at such stages as desired. (Observers should be persons of unusual will power, or of limited athletic interests.) Reference-bar readings are essential. Increases of stress due to cheering activities can be determined by simply holding the gage in place and noting fluctuations in reading as under case *a*.
- d.* Take initial reading, and tighten until the predetermined increase is registered.
- e.* Take readings between metal plugs inserted in the ends of the adjacent slabs when they are in the conditions desired. To interpret the data, careful descriptive records need to be kept. Reference-bar readings are needed since there may be a considerable time lapse between readings.
- f.* Take readings at desired intervals, using both reference bars and temperature records. In all such readings the gage should be left near the structure long enough to assume temperature of immediate environment.
214. *a.* The value assumed for the modulus of elasticity does not agree with the actual value.
- b.* This condition would be a normal one if the applied load included an appreciable axial component. Since the setup was such as to preclude this possibility, the only explanation appears to be that it would have to be due to an accumulation of chance or incidental factors which might be observational inaccuracies or from localized stress concentrations.
- c.* Answer on basis of test data.

Chapter VIII

(See p. 69 for questions.)

Column Tests

215. *a.* 34.7.*b.* 40.

216. No. For tests designed to check theoretical against actual behavior, it is desirable to have conditions of test which are easily attained with reasonable accuracy or assurance. To attain almost complete fixity is difficult. It is not easy to evaluate the degree of fixity present for any intermediate end condition. With reasonable precautions the round or pivot end can be closely approached, and it is therefore the better condition for tests designed to illustrate or demonstrate column action.

217. *a.* Elastic stiffness.*b.* No. Strength controls in the short column.

218. *a.* No. In a beam, up to the proportional limit, the relationship between load and deflection is a function of the modulus of elasticity. In a column there is no clearly defined relationship between load and lateral deflection.

b. The maximum load that can be supported axially on a slender pivot-end elastic column (an Euler column) is a function of the stiffness of the material, *i.e.*, $P = \pi^2 EI/L^2$. For this case E can be evaluated for a given column if P has been determined.

219. Because of the eccentricity of the loading on the column. The eccentricity is not likely to approach a value equal to the semispan of the beams, however, as might at first appear to be possible. See discussion of Question 112, Chap. V, for further consideration of this point. Type of connection and relative stiffness of members determine the actual amount of eccentricity present.

Problem 13

(See p. 71 for questions.)

Tests of Small Timber Columns

220. *a.* The maximum resistance that can be developed by a slender column is a function of its stiffness which is greatest (and constant) within the elastic range of stress. The maximum resistance is developed, therefore, while the stresses are still within the elastic range. It is possible to reach and pass the maximum resistance without damaging the column, simply because the movable head of the testing machine is not free to follow down; otherwise collapse would occur as soon as the maximum load was passed.
- b.* There was redistribution of load; other columns or members assumed the overload; the structure was not statically determinate.
- c.* No. As noted under part *a*, collapse would occur as soon as the ultimate load was reached.
221. *a.* For a slender or Euler column in which the resistance is largely that developed by flexural action.
- b.* A short compressive member under an axial load for which bending or flexural action is negligible.

222. a. Determine from your data.
 b. Lower because of the local imperfections such as knots, cross grain, and lack of straightness which are present in a full-size member to a greater extent than in a small selected specimen.
 c. A knot would probably lower the resistance. While the knot itself might be stronger and stiffer than the other wood, its presence produces eccentricity of resistance which has the same effect as eccentricity of load or a lack of straightness. Besides this effect, there is also some cross grain around the knot which constitutes structural weakness that might promote local failure in that vicinity.
223. a and b. Answer on basis of data secured.
 c. 6.9.
 d. 8.0.
224. Buckling action begins to have an effect on the values of yield strength for slenderness ratios as low as 7 or 8 (h/d ratios about 2), but "column action" does not generally become pronounced until a slenderness ratio of 30 or more is reached, which corresponds to an h/d ratio of 10 or more. The long metal-rod specimen of A.S.T.M. Designation E9-33T has an h/d of 8, and the timber specimens have values from 4 to 5.5. The answer is, then, that the proportions of such specimens may be expected to have a slight bearing upon the relative loads they carry.
225. No. The resistance is determined by the stress of the most stressed portion of the member. The longer member develops more bending and reaches the limiting stress at a lower average load on the specimen.
226. a. Strength.
 b. Stiffness (see discussion under Question 221).
227. a. The total load supported by the column does not change appreciably, and, as the curvature is reversed, one part of the cross section is being relieved of stress as another portion assumes added stress. The transfer or redistribution of the stress requires an expenditure of much less energy than does the application of the load.
 b. No. A well-centered Euler column does not begin to bend appreciably until its maximum (ultimate) load is reached. At that load the deflection may be anything within a considerable range, and the amount of the deflection bears no significant relationship to the load.
228. No. These results are ultimate values rather than working values. The tests are also too few and limited to constitute a proper basis for design. Formulas used in design should have a well-authenticated background of test data sufficiently extensive to insure that practice is not being based upon exceptional or unusual performance.
229. a. Increased.
 b. Increased. Restraint gives added stiffness to the member.
230. a. To minimize end restraint.
 b. No. They would have been stronger because of the stiffening influence of the added end restraint.
 c. No. Usually even a so-called *pin-end column* has considerable end restraint due to friction at the pin. Columns in riveted structures have much end restraint, depending upon the relative stiff-

nesses of the members joined. A flat-end timber column is somewhat restrained, and much restraint is present in reinforced-concrete columns under current construction practice.

231. The small column was straight grained and free from local defects, but it had less of the stiffening influence of end restraint because of the special end fixtures which were used to provide a pin or pivot end.

Chapter IX

(See p. 74 for questions.)

Hardness Tests

232. See Art. 66.
 233. Usually not.
 234. No. Abbott's formula applies only to the tensile strength of steel and some of its alloys, although it gives excellent results for the compressive strength of cast iron. Corresponding relationships could probably be found for other metals, although possibly not for all. It is improbable that a useful relationship between the ultimate tensile strength and hardness could be found for such a material as rubber.
 235. Empirical.
 236. It probably cushions the blow, decreasing the height of the rebound because of the decrease in resilient energy developed by the impact of the falling weight.
 237. a. Kilograms per square millimeter of contact surface (Art. 66).
 b. No, they are simply indexes.
 c. No.
 238. Yes. The fatigue strength of a given metal is related to its elastic and to its ultimate strength, and it seems reasonable, therefore, that the hardness index, which is also related to the ultimate strength, should correlate reasonably well with the endurance limit.
 239. The scleroscope is superior for use on small specimens such as watch springs, the hardened faces of gear teeth, and other fabricated articles that might have their usefulness or appearance impaired by Brinell or Rockwell impressions.
 240. No. It is usually employed as a check on heat treatment, to estimate the strength, or to check on some other quality besides hardness.
 241. A minimum time must be specified, or the load may be removed before the short-time limit of flow, which must precede approximate equilibrium, has been attained and the depression would be undersize (the material would appear to be too hard). The load must not be left on too long for there is likely to be a small additional creep or plastic flow, giving too large an impression. In most cases a few seconds overrun should not be serious since flow occurs slowly after an approximate equilibrium has been attained.

Problem 14

(See p. 74 for questions.)

Hardness Tests

242. No. There is undoubtedly some flattening of the ball while the impression is being made. There must also be a slight elastic recovery of the indented material on release of the load.

243. The impression is smaller; the polished surface provides sharper margins which improve the accuracy of measurement.

244. Less. The bulging relieves the restraint, and for a given pressure a larger hole results.

245. It is essential that the measured flow behavior be the result of action within the specimen. The minimum safe depth for action within the specimen has evidently been set at 10 diameters, presumably on the basis of tests.

a. The hardness index should be too high.

b. The hardness index should be too low.

246. Apply load to a portable Brinell block by means of a lever system, a calibrated jack, or a jack acting through a calibrated spring. Measure the depression, and estimate the strength by Abbott's formula. On horizontal surfaces a scleroscope observation might also be made.

Chapter X

(See p. 79 for questions.)

Fatigue and Impact Tests

247. The modulus of resilience (see Chap. II).

248. No. A high local elongation which is accompanied by a high stress occurs in the immediate vicinity of the fracture. The large amount of work expended on this limited volume is averaged over the entire volume within the gage length, and the apparent absorption of work or energy per unit volume for the entire gage length is much below the maximum unit absorption within the drawn-down or necked area. This point is discussed in Art. 35. There is, moreover, the question of whether or not the strain response to impact loading is properly or fully comparable with that from static loading.

The apparent modulus of toughness, as calculated by dividing the actual energy load required to fracture a specimen by the volume, is generally low because of the localization of stress and deformation which usually accompanies energy loading. Rarely does the energy of impact distribute itself uniformly throughout the volume of a specimen.

The energy required to fracture a dynamically tested specimen never equals the total energy in the hammer or loading mechanism at the instant of contact, since the loading mechanism absorbs some of the energy and some of it is also taken by the supports and holding devices.

249. a. True. The most severely worked portion of the bar is a relatively greater portion of the total volume within the gage length for the shorter gage length.

b. False. Much of the large block absorbs very little energy, the main absorption being along lines of fracture. In pulverizing the fragment, all parts of it are required to absorb energy at a high rate per unit volume. The failure in the fragment is general; in the large block it is localized.

c. (1) False. In spite of the fact that this beam has a greater volume than the other for absorbing energy, the localization of stress and strain caused by the notch will still cause the larger notched beam to fail at an

energy load less than that for the unnotched beam in which the energy is better distributed.

(2) False. The notch localizes the stress and strain causing a concentration of energy at the base of the notch, so that the total energy required to fracture the material is reduced.

250. a. Because it is relatively brittle and neither the hammer nor the steel can absorb much of the energy of the blow without being deformed too much to withstand fracture. The harder piece is the more likely to fail. Grips of a testing machine are especially vulnerable to such treatment.

b. Yes, with a copper or lead hammer or by pounding through a soft metal or a wooden block. The momentum of the blow can be transmitted to the hard steel, but the energy is largely absorbed by the plastic cold-working of the more deformable material.

251. a. At the instant of first contact there is a maximum accumulation of kinetic energy to be absorbed. The moving mass of hammer and all supplementary moving parts, such as the handle and portions of the body of the operator, contribute to the sum total of the energy. During the interval of contact this energy must perform work upon the anvil, the hammer, and incidental portions of the linkage. There will be some rebound which represents the resilient component of the operation. The portions of the anvil and hammer nearest the area of contact will absorb most of the energy by denting and battering. Material a few inches away will be virtually unstrained and unstressed. The portions of the energy of the blow that can properly be allocated to any one of the several units of the linkage (anvil, hammer, handle, person, anvil support) or to the elastic rebound is indeterminate, since these depend upon factors difficult to evaluate, such as relative deformabilities and other details relating to the operation.

b. No. If the anvil is reasonably heavy in comparison with the hammer, the inertia of the anvil will cause the energy to be absorbed near the region of contact and very little effect will be transmitted to the supports for the anvil (in this case the scales).

c. The scale response will depend on the velocity of the hammer and on the relative masses of the anvil and hammer.

d. As indicated previously, the energy is expended inelastically in performing work (creating heat) and elastically by producing rebound.

e. The momentum of the moving hammer is all expended in giving an exactly equal momentum to the opposing masses involved. Since momentum is indestructible (see chapter on impulse and momentum in a textbook on mechanics), the momentum after impact will consist of the momentum of rebound plus a momentum given either to the anvil or to the anvil plus its support. (This may be anything between the

mass of the anvil and the mass of the anvil plus a block of the earth.) A firmly supported, heavy anvil will not acquire much velocity because of the relatively great masses to which the momentum of the moving hammer is being imparted.

- f. When the hammer is pushed downward on the anvil, the case is one of static loading and the entire force of the push is transmitted to the scales as added weight.

252. Yes. Vibration might be considered to be a succession of impacts. Failure from vibration is essentially a failure from repeated impact (impact fatigue). Peaks of stress resulting from vibration are usually within the elastic range, and, if kept below the endurance limit, are not likely to lead to failure.¹

253. a. Frequently. Illustrations are the use of vibration in sieving or screening operations, in placing concrete, and in drilling and stone cutting equipment.

- b. Vibration accelerates breakdown by causing a rapid extension of any form of incipient failure such as that which may accompany a slight inelastic yielding or the formation of a fine crack.

- c. By avoiding abrupt changes in cross section, filleting corners, supplying a sufficient volume of member to absorb the impact energy without overloading, and using recoil and cushioning devices such as springs, pads, and bedments for damping (energy absorption).

- d. Take account of the natural vibration periods of the members and the structure or machine, proportioning the members to avoid resonance and to provide means of damping out and minimizing vibration effects.

- e. Water hammer.

- f. Slow-closing valves, surge tanks, air cushioning, and relief valves.

254. a. There is a greater length to be deformed, and twice the energy can be absorbed at a given stress intensity.

- b. The greater intensity of stress will produce greater elongation, and therefore more work or energy can be absorbed at a corresponding limiting stress (the stress at the reduced section) (see chapter on impact in textbooks on mechanics of materials).

- c. The stress will be approximately uniform along the entire bar instead of having the highest intensity of stress concentrated at the base of the threads, where energy resistance is already lowered by the abrupt changes in cross section and the available volume of highly stressed metal is small.

- d. Only a small part of the volume is subjected to maximum stress and strain. At failure much of the material is absorbing very little of the applied energy.

- e. The energy of the blows is largely expended in local pulverizing of material in the proximity of the hammer rather than in overcoming resistance along major lines of cleavage.

- f. The steel is incapable of withstanding high local deformation because of its brittleness or lack of ductility, and in spite of its great strength its energy resistance is low.

- g. The impact is so rapid that the inertia of the surrounding glass is not overcome. This phenomenon illustrates the high local concentration that normally accompanies an impact load. The "Temple Gun"² constitutes an interesting and potentially useful illustration of the clean, virtually non-tearing, non-bulging penetration which it is possible to secure through the high localization of impact strains.

- h. The candle will be destroyed; the energy of the charge being dissipated in pulverizing the candle and producing local failures in penetrating the board. Nevertheless, the momentum of the candle is not lost, and it or its fragments continue to travel until their momentum has been fully transferred to other objects.

- i. Because of the highly localized resistance offered by water to a suddenly applied load, due to the inertia of water.

- j. From the beginning of application of the load, the full value of the load is acting. A gradually applied load builds up resistance in the material gradually during its application, the average value of the resistance developed being half the final value.

255. a. (1) E23-41T, Metallic Materials.

(2) D256-41, Electrical Insulating Materials.

(3) D3-18, Toughness Test for Rock.

(4) D143-27, Small Clear Specimens of Timber.

(5) D440-37T, Drop Shatter Test for Coal.

(6) D141-23, Drop Shatter Test for Coke.

No. 1 and 2 are of the single-blow Charpy or Izod type.

No. 3 and 4 are of the progressive type.

No. 5 and 6 differ from both of the above tests, the extent of breakage from two or four drops of a 50-lb. sample being used as a basis for a toughness index. The breakage is determined by screening.

- b. Early signs of distress may be recognized.

- c. The successive blows doubtless weaken the specimen before the final blow from maximum height is applied.

256. a. The drop test in which steel rails are dropped from a designated height onto a heavy steel tup.

- b. The flow table for measuring the consistency of concrete provides another type of impact test.

257. a. No. The steel must receive its load through the concrete which is relatively more brittle than the steel. The surrounding concrete affords ample protection against failure of any embedded bar from impact.

¹ For a consideration of supplementary factors bearing upon repeated impact see C. R. Soderberg, Factor of Safety and Working Stress, *Trans. Am. Soc. Mech. Engrs.*, Vol. 52, Part I, Paper APM 52-2, p. 13, 1930.

² Lord, Chester B., Gunpowder Deserts Mars for Vulcan, *American Machinist*, Feb. 6, 1930.

- b. Yes (see Reference *f*, Art. 74, reporting upon impact tests of reinforced-concrete slabs and beams).
- c. Yes. The harder grades of steel must be handled much more carefully since they are subject to breakage while in bar form if handled as roughly as is commonly done for normal grades of steel. The harder grades are also more difficult to bend without breakage.
- 258. a.** 100 per cent if the maximum stress is below the proportional limit since the stress is doubled for a suddenly applied load.
- b. Yes. The loads are not applied instantaneously, there is no height of fall, and it appears that allowances indicated should be ample.
- c. The railway bridge, because the load is much heavier in relationship to the structure. The steel or iron wheels, even on smooth rails, probably impart more impact than do the rubber tires of automobiles. Moreover, the unbalance of the locomotive drivers produces some impact. Tending to counteract these effects is the less smooth surface of the roadway, especially at construction joints.
- d. Yes. The suspension bridge (because of its greater flexibility) can absorb relatively more impact without damage (other things being equal) than can the riveted truss. On the other hand, a reinforced-concrete bridge, while relatively stiff, can absorb considerable impact through sheer massiveness.
- e. Although highway pavement slabs have in the past been designed largely on the basis of static loading, impact and fatigue play an important role in the service to which they are subjected. The conditions near joints are the most critical.
- 259. a.** Because of the time required for a test, the need for results from several specimens tested to failure at several magnitudes of stress makes the endurance limit much less simple to determine.
- b. The progressive nature of the failure exposed the crystal faces along the path of failure, whereas ordinary tests cut across the crystals. The actual structure is not altered in a fatigue or endurance test.
- c. A slight discontinuity or scratch at the surface has been found to offer an excellent foothold for the beginning of a fatigue crack.
- d. More serious because of the high degree to which impact localizes stress and tends to open up cracks and promote their growth.
- 260. a.** Any discontinuity or irregularity which promotes localization of stress. A scratch or a sharp corner is a stress raiser.
- b. A crack which probably starts within the rail from too rapid cooling and which gradually works across the section of the rail, producing fracture if not detected in time.
- c. A transverse fissure is a failure across the rail, usually having originated from a shatter crack. Fatigue and impact probably both play an important part in the development of transverse fissures.
- d. See discussion in Chap. X.
- e. Used in connection with repeated loading in which each outside fiber is alternately under tension and compression. The rotating beam type of specimen is commonly used for reversed bending tests.
- f. See Question 259b.
- g and h. Fatigue strength and endurance limit may both be defined as "the highest unit stress to which the material may be subjected for many millions of repetitions of stress without failure."
- 261.** Yes, at about 50 per cent of the ultimate strength.
- 262. a.** Yes.
- b. The stress is relatively high being above the elastic and endurance limits.
- 263.** The worn portion is that portion through which failure progressed gradually. Successive repetitions wore the contact faces smooth. The central portion failed suddenly after the section had been weakened sufficiently from the progressive fracture.
- 264.** Fatigue is much the more important for the steam turbine which has many times the number of repetitions of stress.
- 265. a.** Lower.
- b. Nonproportional action starts locally at a stress well below that corresponding to the generally recognized proportional limit. Any nonproportional action, even though small, creates a condition favorable to the formation of infinitesimal cracks, and even such cracks assume importance as foci for progressive breakdown from repeated stress.³

Problem 15

(See p. 81 for questions.)

Standard Impact Test of Metal

- 266.** The center of percussion of a rotating body is the point at which a normal force may be applied without producing a normal force at the center of rotation.
- 267.** See textbooks on analytical mechanics.
- 268.** The concentration of energy will be greatest in the vicinity of the notch and will be relatively small near the ends of the specimens.
- 269.** The modulus of toughness is evaluated on the assumption that the energy is uniformly distributed throughout the specimen. A concentration of energy at the notch is accompanied by (or is a result of) a concentration of stress in the same area. Hence less energy is required to produce the ultimate stress in the vicinity of the notch than is required to stress the entire volume to the ultimate.
- 270.** An increase in the radius of curvature of the base of the notch will result in a higher toughness index; the energy of the blow is less localized.
- 271.** To prevent fouling the pendulum.

³ Splendid illustrations of fatigue failures and an extensive bibliography on fatigue are included in a recent book: "Prevention of the Failure of Metals Under Repeated Stress," by Staff of Battelle Memorial Institute. John Wiley and Sons, Inc., New York, 1941. Prepared for the Bureau of Aeronautics, Navy Dept. under auspices National Research Council.

Problem 16

(See p. 82 for questions.)

Impact Test of a Timber Beam

272. The proportional limit may be determined if the modulus of elasticity of the material is first evaluated from the static loading. The deflection at the proportional limit may be determined from the graph sheet as the deflection at the end of the initial straight-line portion. The equivalent static load which would produce that deflection may be calculated, and the proportional limit evaluated as the corresponding stress.

273. The modulus of resilience of the material can be evaluated from the proportional limit and the modulus of elasticity.

274. The equivalent static load is that gradually applied load which would produce the same deflection as the impact load.

275. The energy is not uniformly distributed throughout the beam at fracture. Only the extreme fibers in the region of maximum moment are stressed and deformed the maximum possible amount (absorbing energy at the rate that produces failure).

276. More. After the proportional limit of the most stressed fibers is passed, each additional drop contributes toward progressive breakdown which decreases the severity of final blow required.

277. Not only does timber have high resilience per pound of weight, but it is capable of withstanding repeated impact stresses above the proportional limit without undue deterioration. Timber has good cushioning quality and can absorb considerable local battering without extended general damage. This, combined with its capacity for withstanding impact in both the elastic and the inelastic ranges and in combinations of the two, contributes greatly to the usefulness of timber as a structural material.

Problem 17

(See p. 82 for questions.)

Endurance Test of Metal

278. a. Steel, copper, brass, cast iron, and most other metals.

b. Aluminum and the aluminum alloys.

c. For the endurance limit of the aluminum alloys the Aluminum Company of America uses the maximum stress which may be applied 500,000-000 times without fracture. This is analogous to the procedure used in evaluating "creep limit" for materials in which the property of creep is ill-defined (see creep limit in a textbook on properties of materials).

279. Approximately the same.

280. Little or no effect.

281. Answer on basis of test results.

282. 695 months or 58 years.

Chapter XI

(See p. 104 for questions.)

Design, Control, and Curing of Concrete Mixtures

283. Other major building materials are manufactured, and their quality is usually checked before they come to the

job. They are ready to be placed in the structure. With the exception of concrete, only secondary materials such as plaster, mortar, and sometimes paint are mixed or manufactured on the job.

284. a. The quality of the hardened concrete cannot be checked before the concrete has actually become an integral part of the structure. Any required replacements are relatively difficult and expensive to make. Obviously then, every reasonable precaution needs to be taken in advance to insure concrete of acceptable quality.

b. The difference is more one of degree than of kind. The strength of a concrete member is not fully developed for days or weeks after placement in the structure, while the strength of a steel or timber member does not become available until after it has undergone the field operations of connecting it to the surrounding members with which it functions to resist loads. In both cases the actual strength and serviceability can be ascertained only after the completion of the field operations which make the member an integral part of the structure. In either case the correction of faulty design or manipulation becomes a difficult and costly operation. In both cases good design followed by close adherence to the tenets of good job practice will assure a proper structure with about equal certainty.

285. See Art. 75.

286. a. The term *control* refers to those measures which are taken during mixing and placing operations, and subsequent thereto, to insure the desired uniformity and quality of hardened concrete in the structure. As one of the important control measures, compressive or flexural specimens (or both) of representative samples of the concrete are cast at intervals as placement progresses in accordance with A.S.T.M. Designation C31-39 or C94-41T.

b. Specimens used for "quality control" are stored moist under standard conditions (see A.S.T.M. Designation C39-39 and C31-39) and are tested at a specified age, usually 28 days. Specimens allocated to "job control" are fabricated just as are the others but are stored on the job, simulating as far as is possible the same environmental conditions of moisture and temperature as those to which the concrete in the structure is exposed.

c. The quality-control specimens represent the quality of the concrete that went into the structure. They give no indication of the quality of the hardened concrete in the structure in so far as this may have been affected by factors subsequent to placement, primarily the moisture and temperature conditions. The results of the tests indicate the strengths which the concrete as mixed did develop under favorable and controlled conditions of curing.

d. The job-control specimens are expected to represent the quality of the hardened concrete in the structure, the test results being influenced

by both the quality of the mixture and the subsequent curing or lack of curing. The disadvantages of job-control specimens arise primarily from the difficulty of insuring that temperature and moisture conditions (both of which are very important), actually do approximate those of the structure. Even when cured side by side, the moisture, evaporation, and temperature changes that occur in a small isolated volume of concrete may differ greatly from the conditions which exist within a hardening mass. If the job-control specimens give poor results, it may be difficult to determine whether the deficiency was because of a poor mixture or of poor curing subsequent to placement.

- e. The quality-control specimen is generally to be preferred. The moisture and temperature conditions necessary to insure good curing are well known and can be enforced rather easily with good results practically assured. The quality-control specimens check the concrete for imperfections that might arise from such sources as deficiency of cement, poor quality of cement, inferior aggregate, and an improper mixture. When used, the job-control specimens should generally be for supplementary rather than primary control. Job-control specimens are sometimes used to assist in reaching a decision upon when to admit traffic upon a new stretch of pavement or when to strip forms or to place a portion of a structure into service. Drilled cores from the hardened concrete for compressive testing constitute an excellent but usually costly form of job control (see A.S.T.M. Designation C42-39).
287. a. Strength is not only important in its own right but also as an excellent criterion of several of the more desirable properties of most concrete, such as imperviousness and durability. Strength is unimportant only for concrete of low quality used primarily as filler material:
- b. Economy is always desirable, but the saving of a few cents or even a few dollars per cubic yard may be of little consequence if the volume is small; it may be of great importance where hundreds or thousands of cubic yards are involved.
 - c. Consistency and workability need always to be appropriate to the job. Thin, heavily reinforced sections require relatively fluid, fat mixtures to prevent honeycombing and high porosity. Where vibrators are used or methods are such as to insure adequate placement, the quality can be maintained and economy promoted by using stiffer and somewhat harsher mixtures (less cement) than would be possible or desirable otherwise.
 - d. Durability is an over-all term denoting resistance to a variety of factors, two or more of which are often simultaneously at work. Among the manifestations of durability are the following:
 - (1) Resistance to *abrasion* which is not generally of primary importance in these days of rubber-tired traffic, but it may be of great importance in special situations, such as where the concrete is to be subjected to the impact of water jets, to flowing water at high velocity, or to ice scour.
 - (2) Resistance to *weathering* which is especially important for thin sections exposed to severe weather conditions. Weathering attack is due mainly to the volumetric changes that accompany the vagaries of weather (alternations of hot and cold, of freezing and thawing, and of wet and dry). Differential movements progressively break the bond between cement and particles of aggregate, working from the surface inward. Slab and thin-arch or multiple-arch dams, river and canal structures, and exposed railings are illustrative of structures in which resistance to weathering is especially important.
 - (3) Resistance to *chemical attack* which is especially important in marine structures exposed to sea water, concrete exposed to alkali attack, and concrete in some industrial situations. Concrete sewers and silos also face such attack, as does concrete where salt is used for snow removal.
 - (4) Resistance to *permeability*. Resistance to leakage is often important in its own right as in the case of thin dams, of retaining walls, of basement walls and floors, and in tanks. Continued leakage of water through concrete is always objectionable, however, because soluble portions are leached out progressively, resulting frequently in severe damage and ultimate breakdown. Impervious concrete is safe against any but the most severe chemical or weathering attack.
 - e. Volume change (swelling and shrinking) may result from a variety of causes, several of which were mentioned above under weathering. Swelling from the chemical heat of hydration and subsequent shrinkage upon cooling is a form of volume change extremely important for concrete masses and of no consequence for nonmassive concrete such as that used in pavements and ordinary construction. This form of volume change occurs in the two phases of a single cycle (one heating and one cooling), and, instead of attacking solely from the surface, it forms large shrinkage cracks analogous to those which sometimes occur in a large casting upon cooling. These develop at various places throughout the mass, often more or less concentrically. In ordinary structures the heat of hydration is dissipated about as rapidly as it is generated, and the temperature of the interior concrete is elevated but little. But in massive concrete the heat cannot escape readily, and the interior temperatures often rise as much as 60 or 70 F. within a few days or weeks after placement. For a pavement slab the most important volume change is that from longitudinal shrinkage as the pavement dries out. For exposed walls, floors, and other areas "map cracking," "hair cracking," or "checking" may

occur from shrinkage in all directions. Map cracking is often a symptom of destructive volume change from the swelling that accompanies the chemical deterioration of unstable aggregate. Some forms of chert as aggregate are subject to destructive expansion. In other cases cements with a higher than average alkali content have reacted adversely with certain mineral aggregates which are usually stable. The swelling of hardened concrete from any cause other than an increase in temperature or moisture content is invariably an accompaniment of chemical deterioration. Thus volume change may be either a physical or a chemical phenomenon; in either case it is important in its relationship to durability. A rich mixture undergoes greater volume change than a lean one under changes in moisture content, and one frequent form of destructive volume change is differential movement between a rich mortar topping layer and its leaner base. To avoid this, single-course construction has been found better for pavements, sidewalks, and handrails than the former procedure of topping off with a relatively rich surface layer of mortar.

- f. Heat of hydration varies in amount with the type and relative amount of portland cement used. Its importance is mainly limited to mass concrete, the reasons for this having been discussed under volume change.
- g. Plastic flow or creep under sustained loading produces redistribution of stresses between the concrete and reinforcing steel in reinforced members such as columns and beams. Under sustained loading, concrete may deform several times as far as would have produced failure under ordinary short-time loading. In members which are drying out following moist curing, plastic flow and drying shrinkage are often occurring simultaneously, and it may be difficult or impossible to differentiate between the two.
- h. Appearance is most important in architectural concrete. It is quite important, however, in the exposed faces of any important structure.

288. No. The durability of much concrete construction is below that of the concrete itself because of contributing environmental factors. One illustration is the effect of subgrade movements from freezing and thawing which heave and twist pavement and sidewalk slabs producing initial cracking and extending existing or incipient cracks. Overstress from static, impact, or fatigue loads, additional to those recognized and taken account of in the design, may break down concrete of excellent inherent quality. A failure to provide properly located expansion and contraction joints frequently produces initial cracking which leads to raveling and progressive breakdown, although the concrete itself may be of excellent quality and relatively durable.

289. a. As initially stated by Abrams,¹ the "law" is worded as follows: "With given concrete materials and conditions of test the quantity of

mixing water used determines the strength of the concrete, so long as the mix is of a workable plasticity." The current Portland Cement Association version of "Abrams's law"² is as follows: "For plastic mixtures, using sound and clean aggregates, the strength and other desirable properties of concrete under given job conditions are governed by the net quantity of mixing water used per sack of cement."

- b. The aggregate is assumed to be inert filler which economizes on cement-water paste without adding or subtracting from the potential strength of the mixture.
 - c. Yes. Variations of grading and amounts of approved aggregates may, for plastic mixtures, all at a constant water-cement ratio, produce mixtures that vary 50 per cent or more in strength. References supplying evidence of this may be found on p. 279, *Proc. A.S.T.M.*, Vol. 38, Part I, 1938. Firsthand evidence of variations in strength "within the law" are likely to be secured from the comparative test results from the several batches of Series II and III of the outlined tests. All the batches of both series are at identical water-cement ratios, and, according to the law, the workable mixtures should produce specimens of equal strengths at comparable ages and curings.
 - d. No. Within the range of gradings and proportions for most of the concrete used in building construction and paving, the water-cement-ratio law constitutes an excellent criterion for predicting strengths. It is valuable as the most widely used current basis for the design of concrete mixtures and much credit is due to Abrams for having recognized the relationship and for giving expression to it.
290. a. Feret, an eminent French scientist and engineer, introduced the voids-cement concept, primarily applied to mortars prior to the work of Abrams on water-cement ratio in this country. Talbot and Richart introduced the voids-cement ratio in this country shortly after the first publication of Abrams' work.
- b. Within the range of plastic mixtures the voids-cement ratio is virtually identical with water-cement ratio. The voids consist of the net water plus air, and in plastic mixtures the air is almost if not entirely negligible. This is shown in the illustrative calculations. Since there are usually some air voids, the voids-cement ratio, expressed in the same units, will be slightly larger than, but parallel to, the water-cement ratio.
 - c. Essentially the same variations are inherent within the voids-cement-ratio law, as within the water-cement-ratio law.
 - d. The concept of absolute volumes was introduced by Talbot and Richart in their exposition of the voids-cement-ratio technique of design. The use of absolute volumes is basic and represents a

¹ Abrams, Duff A. *Design of Concrete Mixtures, Structural Materials Research Laboratory Bull. 1*, Lewis Institute, Chicago, 1918.

² *Design and Control of Concrete Mixtures, Portland Cement Assoc. Bull. T-12* (Chicago), 7th ed., p. 6, 1940.

substantial advance in concrete thought and practice.

291. a. (1) Soon after the placement of plastic concrete, before hydration has progressed far enough to stiffen the mixture, water begins to gather at the surface and continues to accumulate for an hour or more until the initial set or stiffening occurs. The "water gain," or "bleeding," as it may be called, is purely physical, being the result of the natural sedimentation that causes solids to settle and water to rise as long as the mixture is mobile. Water may also vary due to leakage from the forms, evaporation, absorption by the forms, or uncorrected absorption or free moisture in the aggregate. The amount of cement being constant, the water-cement ratio is altered with every fluctuation in the moisture content. The voids change with the water, for as water is lost, particles are drawn closer together and any gain in the water within the mass expands or spreads the mixture.
- (2) The effective water-cement ratio, the one which influences the strength developed, is that of the mixture when it ceases to be mobile, for at that stage the particles are fixed with respect to one another. After the mixture has stiffened, loss of free moisture will no longer decrease voids; the spacing of the solid particles is no longer a function of the water content. A change in water content that does not "contract" or "spread" the mixture is meaningless as regards water-cement ratio and also as regards voids-cement ratio.
- b. Yes. One of the fairly recent developments in the technique of concrete placement is to use ample mixing water for ease of placement after which the water-cement ratio (and voids-cement ratio) is lowered by extracting the excess water while the concrete is still plastic enough to be more closely packed thereby. The vacuum process extracts water by suction; and absorbent forms have been used with much success. The vibrolithic process of pavement construction vibrates and rolls extra aggregate into the surface of the concrete as the water and some of the cement are brought to the surface by vigorous vibratory tamping. This method has a favorable influence on both strength and yield.
- c. Usually not. If the concrete is partially dry, some of the water voids are air voids. Even if saturated, especially if there has been an intermediate period of exposure to dry air, many of the capillary passages in the concrete will contain entrapped air that is not dislodged by moisture.
- d. No. The processes of hydration involve crystal growth and the formation of gels that must greatly alter the volume as well as the nature and arrangement of the voids spaces in the concrete.
- e. (1) For the reasons given under part c.
- (2) In addition to the previous consideration the small capillary passages have a powerful affinity for water and some of this water will be held in small capillaries even after the temperature has been elevated sufficiently to produce partial dehydration of crystalline constituents. There is, therefore, no stage in the drying process at which the uncombined or free water, and that only, can be considered to have been evaporated from the concrete.
292. a. In its details the hydration of portland cement is an involved process regarding which many questions remain unanswered. Nontechnically the process may be explained as one of crystal and gel formation. Crystals of four primary compounds are formed in addition to various gels. These gels as they exist in concrete, in minute concentrations, function much differently than does jelly as we picture it, just as water in thin films or in small capillary passages displays such properties as great tensile strength, low freezing point, and great resistance to evaporation. The hardening of cement and concrete is the opposite of drying out since the presence of moisture is necessary for both crystal and gel formation.
- b. The presence of moisture and moderate temperature are essential to the hydration of portland cement. The hydration is retarded as the temperature is lowered and ceases at a few degrees below the freezing point of water. Hydration is retarded with lack of moisture and ceases altogether when additional moisture becomes unavailable. Hydration will resume when moisture and favorable temperatures again become available. For moisture effects see Figs. 24 and 25.
- c. (1) In concrete frozen immediately after placement, hydration is at a standstill. Such concrete will harden satisfactorily, but slowly, if favorable conditions for curing are maintained after it has been thawed.
- (2) Concrete frozen a few hours after placement may be damaged severely. The free water freezes, swells, and disrupts the concrete neutralizing whatever strength had been acquired from early curing. Such concrete will, if kept moist at a favorable temperature, eventually develop much of its potential strength.
- (3) It usually requires repeated freezings and thawings to damage well-hardened concrete visibly. Most of the free water is now in small capillary passages being more or less immune to freezing under these conditions.
- d. No. The curing or hydration of concrete continues under favorable conditions of moisture and temperature at a diminishing rate for years. At 7 days ordinary portland-cement concrete under standard curing may be expected to develop from 50 to 70 per cent of its 28-day

strength, and at 28 days it may be expected to have 40 to 60 per cent of the strength attainable in a year of favorable curing. Hydration starts first with the finest particles of the cement to form the more rapidly formed compounds, tricalcium aluminate being the earliest. With the lapse of time larger (but still microscopic) particles of cement are hydrated, and some of the later compounds are formed. Relatively coarse particles of cement may never hydrate sufficiently to form useful compounds.

- e. Analytical studies seem to indicate that the water required to lubricate the mixture (to supply enough workability for placement) exceeds that required to hydrate the cement. In spite of this, concrete sealed against moisture loss or gain will hydrate only for a period of a few weeks or months. The hydration in its later stages is retarded or halted if added water is not supplied. One reason for this may be that not all the capillary free water in the concrete is available to the cement for hydration purposes.
 - f. No. Timber, porous stone, brick, tile, etc., are all weaker when saturated than when air-dry throughout. The moisture doubtless softens up some of the colloids and lubricates the mass, making it offer less resistance to the relative movement of particles. The dry condition, in any case, must be more or less general and uniform throughout the mass, as must also the wet condition. The dry condition for maximum strength requires days or weeks of exposure, depending upon the size of the specimen and the humidity of the air. For concrete the wet condition is usually attainable by 12 to 24 hr. of immersion.
 - g. No. Oven-drying weakens concrete as much or more than the drying strengthens it. Some tests of oven-dried specimens show them to be weaker than similar specimens in the moist condition; other tests show them to have about the same strength, when tested dry, as do the normal specimens moist at test. In any case, if the oven-dried specimens are immersed 12 to 24 hr. prior to test, the strengths from them are from 15 to 30 per cent below those of the undried specimens moist at test.
 - h. In drying out, pavement concrete will shrink perhaps $\frac{1}{8}$ in. in 100 ft., whereas molding clay will shrink from 8 to 12 ft. in 100 ft. (8 to 12 per cent against about 0.04 per cent, or a ratio of about 250:1).
 - i. (1) Initial moist curing is relatively unimportant for the dam. High-early-strength development is not essential, the structure is massive and will retain most of its mixing water, and it will be moist during much of its period of service; hence it will eventually be well cured.
(2) The pavement slab will be subjected to rain, snow, and a moist subgrade; hence it will eventually become well cured. But it needs preliminary curing nevertheless, in order to develop a maximum of strength before having to support traffic. If left for the ultimate favorable curing, it might in the meantime be seriously damaged by overstress.
 - (3) The initial curing is very important for the building, for it will probably be dry throughout its period of service and may never have a chance to develop a strength beyond that imparted by the initial moist-curing period. In winter freshly cast concrete is sometimes seriously weakened by supplying heat to prevent freezing without supplying the moisture needed for hydration.
293. a. If batches are weighed, no allowance need be made for bulking of the fine aggregate. Allowance needs to be made, however, for the free moisture that produces the bulking. If batches are measured by bulk or loose volume, bulking, if uncorrected, will cause too little sand to be in the mixture. The free water that causes the bulking also requires correction.
 - b. If the specific gravity is higher than the true value, too little of the material will be used (assuming measurements by weight). The lower the specific gravity, the greater will be the volume of a given material corresponding to a given weight.
 - c. No. No such degree of refinement is warranted in actual proportioning for job purposes. The extra significant figures are carried in order to get better closures and cross checks. These are not usually of much practical concern.
 294. a. See text.
 - b. See text.
 - c. (1) By spreading the aggregate out in thin layers in pans or on a clean floor for a few hours prior to use, thereby bringing it to the saturated surface-dry condition.
(2) By ascertaining the amount of free water in accordance with some such method as A.S.T.M. Designation C70-30 and correcting the weights of mixing water and fine aggregate accordingly after the manner outlined in the illustrative examples.
 295. a. See text.
 - b. When the fine aggregate is measured by volume rather than weighed.
 - c. By measuring materials by weight; by correcting quantities of fine aggregate and water for the errors introduced by the bulking; and by use of an inundator (making volumetric measurements of submerged or inundated aggregate. Aggregate is never bulked when in either the inundated or the dry condition).
 296. a. It extracts water from the mixture.
 - b. Usually for the coarse aggregate, because of the larger quantity of it. If the fine and coarse aggregates are of similar materials, their percentages of absorption will not differ greatly. Often the material of the coarse aggregate is more absorptive than that of the fine aggregate.

- c. (1) By bringing the aggregates to the saturated (or partially saturated) surface-dry condition by soaking and draining prior to use.
 - (2) By adding enough water to the mixing water to correct for the absorption by the aggregates.
 - d. The function of the mixing water is to lubricate the mixture, to provide the workability for placement. As soon as the concrete is in place the need for workability is past. Added absorption is not then likely to be of consequence, since the excess from the mixing water more than provides for early curing needs until added moisture for curing is forthcoming from the moist storage that should always be supplied. Moreover, most aggregates will attain, in the first few moments of soaking, a high percentage of their ultimate absorption.
297. a. As the necessary basis for computing absolute volumes.
- b. The specific gravity should be that for the aggregate as it is weighed out for the batches. Otherwise the weights used will not conform to those on which the design was based.
298. The "probable strength in pounds per square inch per bag of cement per cubic yard of concrete" is simply a convenient index for checking on the relative effectiveness of the cement in different mixtures. The comparison is interesting but relatively unimportant since the actual economy of the mixture is usually outweighed by other factors.
299. a. (1) Recognition that, within the limits set by a general definition for portland cement, controlled variations may be introduced which will improve the quality of the resulting concretes for specific uses.

The currently recognized variations are five in number and the single unified A.S.T.M. Designation C150, which replaces C9 for Type I and C74 for Type III, has been formulated to include, in addition, three types for which the need has become acute.

"Type I—For use in general concrete construction when the special properties specified for types II, III, IV, and V are not required.

"Type II—For use in general concrete construction exposed to moderate sulfate action or where moderate heat of hydration is required.

"Type III—For use when high early strength is required.

"Type IV—For use when a low heat of hydration is required (note).

"Type V—For use when high sulfate resistance is required (note).

"NOTE: Attention is called to the fact that cements conforming to the requirements for type IV and type V are not usually carried in stock. In advance of specifying their use, purchasers or their representatives

should determine whether these types of cement are, or can be made available."

- (2) A recognition that cement as manufactured may not have the ultimate of attainable desired properties for specific applications but that still further improvement may be possible through the use of additions (or admixtures)³ to be added at the purchaser's option.

- b. The composition, constitution, and use of Natural Cement, Keene's Cement, and Masonry Cement places them outside of any of the accepted standard portland cements. They cannot qualify under the general definition of portland cement.

c. Type I.

- d. (1) In the light of current knowledge the test should represent the best means (as judged by simplicity of procedure and positiveness of results) for checking upon some essential specified chemical characteristic of the cement. The test should be essential, and it should be adequate.
- (2) The results from the test should correlate satisfactorily with the concrete-making properties of the cement.
- (3) Specific surface as determined by the turbidimeter (A.S.T.M. Designation C115) has been adopted as the criterion for fineness instead of the percentage passing the 200-mesh sieve. Obviously, the specific surface is much the more discriminating measure of fineness. A compressive test from a plastic mortar made with a graded sand may optionally be specified in lieu of, or in addition to, the longstanding 1:3 stiff standard-sand (20 to 30 grading) tensile briquet, made at a water content based on the normal consistency of the cement.

The autoclave expansion test (A.S.T.M. Designation C151) has been substituted for the small soundness pat as a test for soundness.

- e. The published annual reports of the A.S.T.M. committee on a particular material usually supply excellent indications of developments in progress several years before an actual standard is evolved. For portland cement Committee C-1 has jurisdiction. Other of the current literature listed after Chap. XI constitute excellent supplementary sources of information.

300. No. It has long been known that some forms of chert are subject to disintegration in concrete, especially if within a few inches of the surface. Recently certain andesitic rocks in the southwest, and other rocks in California and Washington, have been found to react unfavorably.

³ An addition is defined as any material interground with the cement in an amount usually below 1 per cent of the weight of the cement. An admixture is something to be added to the concrete, usually during or just prior to mixing. The addition may be as a "grinding aid" to decrease cost of grinding, a plasticizer, or as something to develop some other alleged desirable property in the concrete. The admixture may be to increase the workability or for other specific or general purposes. In cement specifications cognizance can be taken of additions only since admixtures relate to concrete rather than to the cement.

bly with some cements. Extensive researches are under way in an effort to determine the causes. There is some evidence that a slight excess of certain alkalies in the cement may be an important factor. The subject is extremely important and needs to be followed up in the literature as the results from the current researches are released, since serious deterioration has developed in some important structures which were constructed by the best known methods under rigorous control. Papers by Blanks⁴ and Stanton⁵ show the seriousness of the problem which is now actively under investigation by cement companies and government laboratories.

301. a. No. Voids in general do not make durable concrete. This has been demonstrated repeatedly by the lack of strength, as well as of ability of high-void concrete (notably concrete which had a high water-cement ratio) to resist severe exposure. If, therefore, certain admixtures or additions which increase the air voids (expand the mixture, without requiring extra mixing water) do result in greater durability, it must be because they produce a more favorable type of cell or voids structure than is produced either by excess water or the ordinary honeycombing which accompanies unworkability. Whether the minute void spaces occur as connected passages or as separate closed pores may have a significant bearing upon the phenomenon of deterioration under certain types of exposure. Dense concrete retards deterioration by limiting the depth and amount of penetration of injurious chemicals or of moisture which may subsequently freeze. Perhaps a cellular porosity (as distinguished from continuous or capillary porosity) might also limit penetration and in addition provide some cushioning against the wedging action which must occur as water freezes or as chemical salts or crystals form and expand.⁶

The previous concepts regarding the merits of low-void concrete are sound, but it appears that some of our beliefs relative to the evils of high-void concrete may require qualification in the light of the recent data which supplement, but do not necessarily conflict with, previous findings.

b. For highway pavement slabs in cold climates, especially where salt or calcium chloride is used for ice and snow removal, the sacrifice of some strength for added resistance to frost and salt action would be fully justified.

Problem 18

(See p. 110 for questions.)

Design of Concrete Mixtures

302. a. As explained in Chap. XI, workability is the over-all term used to designate the placing

⁴ Blanks, R. F., Concrete Deterioration at Parker Dam, *Eng. News-Record*, Vol. 126, pp. 462-465, Mar. 27, 1941.

⁵ Stanton, Thomas E., Expansion of Concrete Through Reaction Between Cement and Aggregate, *Proc. Am. Soc. Civil Engrs.*, Vol. 66, No. 10, pp. 1781-1811, December, 1940.

⁶ Swayze, M. A., More Durable Concrete With Treated Cement, *Eng. News-Record*, Vol. 126, No. 25, pp. 946-949, June 19, 1941.

quality of the mixture. It may be broken down into consistency, the measure of stiffness (or inverse measure of fluidity) and texture, the measure of cohesiveness and plasticity, or apparent homogeneity. If the workability is right, both the consistency and the texture must be right.

b. Harsh, plastic, and fat represent three degrees of variation in texture. A harsh mixture has an excess of coarse material and is lacking in fine aggregate and/or cement. It lacks cohesiveness and homogeneity; it bleeds (water separates easily from the mass), unless the relative water content is very low; it segregates easily and falls apart rather than slumps. A plastic mixture has good cohesiveness, resembles a viscous fluid in its behavior and has little tendency to bleed or segregate. On the other hand, it has little excess of fine material beyond that required to unify the mass. A fat mixture has a noticeable excess of cement and/or relatively fine sand; its texture is so fine as to be almost like lard or grease. When slapped a few times with a trowel, the plastic and fat mixtures show smooth even surfaces, whereas a harsh mixture will present a flat surface interspersed with hollows or empty pockets. Generally speaking, texture is independent of consistency and a plastic or a fat mixture may have a slump of anything from zero upward. The stiffness of a harsh mixture is less easily measured, because those which are very harsh neither slump nor flow—they simply fall apart.

c. Slump is an inverse measure of consistency, the greater the slump, the lower is the consistency. Flow is also an inverse measure of consistency. Both of these measures of consistency are more discriminating over some portions of the consistency range than over others, and the most effective range is not the same for the two kinds of measuring device. The slump test is the simpler and more widely used. Results from flow tests may be influenced appreciably by the type of flow-table support which affects the proportion of the energy of drop absorbed by the sample. Texture can be evaluated only by eye, its measurement being one of the items that still must be classified as an art rather than a science.

303. a. Adding or extracting water will vary the consistency and the strength (since it alters the water-cement ratio), but it should not alter the texture.

b. By adding or extracting aggregate, the consistency may be varied without altering the predicted strength; the texture may be changed or unchanged, depending upon the relationship maintained between fine and coarse aggregate.

c. By the application of Lyse's approximation, interchanging cement and fine aggregate, the strength may be varied at constant workability.

d. By increasing both the water-cement ratio and the amount of aggregate, the yield may be

- increased at the expense of strength but without loss of workability, providing the proper balance is maintained between coarse and fine aggregate.
- Yes, by adding aggregate to a given amount of paste. This will be at the expense of workability.
 - Yes, to a limited extent
 - By changing the shape of particle from angular to rounded.
 - By improving the grading of the aggregates.
 - By increasing the maximum size of graded aggregate (see Fig. 27 for use of greatly increased amounts of coarse aggregate although at some decrease in workability).
- 304. a.** The stiff mixture has the greater yield (is the more economical) because it contains more aggregate per unit of cement-water paste.
- b.** Thin, heavily reinforced sections or otherwise inaccessible locations, which make spading and tamping difficult, often necessitate the use of mixtures which will flow into place with a minimum possibility of bridging or honeycombing.
- (2) No. See more detailed consideration under discussion of Question 307, Prob. 19.
- See Chap. XI.
 - Answer on basis of your evidence.
 - By substituting cement for all the fine aggregate for one mixture and fine aggregate for all the cement for another mixture. These are the two limiting cases. The substitutions can be made either by absolute volumes or by weights.
 - Yes, Mixtures 4 to 7 of Series I.
 - By mixing two trial batches, corresponding to Batches 6 and 7 of Series I as outlined in Chap. XI.
 - No. The finer the sand the wider should be the valid range, because of the greater similarity between the cement and the fine aggregate.
- 306. a.** At best such a rule is but an approximation that may be expected to vary with the characteristics of the aggregates as well as with the water content.
- b.** Answer on the basis of the data secured.

INTERCHANGE OF ABSOLUTE VOLUMES

	Batch No. (Series I)				
	1	2 (base)	3	4	5
Design strength, p.s.i.....	4900	3000	1700	.....	0
c/w abs. vol.....	0.70	0.50	0.40	2.00	0
Cem. (given) (c).....	0.140	0.100	0.080	0.400	0
F.A. (a).....	0.260	0.300	0.320	.....	0.400
C.A. (given) (b).....	0.400	0.400	0.400	0.400	0.400
Water (given) (w).....	0.200	0.200	0.200	0.200	0.200
Total.....	1.000	1.000	1.000	1.000	1.000
Proportion (abs. vol.).....	1:1.86:2.86	1:3.00:4.00	1:4.00:5.00	1:0.00:1.00	0:4.00:4.00

- c.** No. The lack of economy is secondary. Thin mixtures promote segregation and "water gain." The larger particles settle, and the water and finer material rise to the surface as laitance. While thin mixtures fit the forms closely and are often of excellent appearance, they are really inferior to what the same mixture would be with enough more aggregate to make it plastic rather than fluid. The high water content per unit of volume increases the amount of drying shrinkage; the void-content is high and the thin mixture is less homogeneous than the plastic one.

- 305. a.** The smaller the particle size of material, the greater is its specific surface (surface-volume ratio), and the greater is its thickening power. Thus, per unit of absolute volume, the cement has the greatest thickening capacity (or influence on the water requirement for lubrication of the mixture), and the coarse aggregate has the least influence.
- b.** (1) Yes, indirectly because of the usual difference between the specific gravity of cement and that of the fine aggregate.

Problem 19

(See p. 115 for questions.)

Comparisons of Concrete Mixtures and Curings

- 307. a.** (See tabulation above.)

With b known a alone remains to be determined.

$$b + w = 0.60. \text{ Then } a + c = 0.40 \text{ and } a = 0.40 - c.$$

- b.** No. These are both trial batches from which the value of c or a that will give the specified workability are to be determined by experiment.
- c.** For a given change in absolute volume of cement, the absolute volume of an equal weight of the fine aggregate will be $3.15/2.65$ times the absolute volume of the cement which is added or subtracted. Thus for Batch 1 the cement has been increased 0.04 above that for the base batch which calls for a decrease in fine aggregate of $(3.15/2.65)0.04 = 0.048$. Then for this batch $a = 0.300 - 0.048 = 0.252$. For Batch 4 the fine aggregate is entirely replaced by cement.

Thus

$$c = 0.100 + 0.300(2.65/3.15) = 0.100 + 0.252 \\ = 0.352.$$

For Batch 5 the cement is entirely replaced by fine aggregate. Thus

$$a = 0.100(3.15/2.65) + 0.300 = 0.119 + 0.300 \\ = 0.419.$$

slight differences resulting from the two possible techniques of its application for aggregates with specific gravities above 2.50.

f. Normally interchange by weight would be the simpler for job use, in which case it should be employed.

g. Yes. For the two methods of interchange the cement-water ratios for Batch 4 are 2.00 and 1.76, respectively. Equivalent water-cement ratios

BATCH QUANTITIES BY ABSOLUTE VOLUME FOR SERIES I

Basis of interchange of cement and fine aggregate being equal parts by weight instead of by equal parts absolute volume as in 307a. Ratios c/w same as in 307a

	Batch No. (Series I)				
	1	2 (base)	3	4	5
Design strength, p.s.i.....	4900	3000	1700	.....	0
c/w abs. vol.....	0.70	0.50	0.40	1.76	0
Cem. (given) (c).....	0.140	0.100	0.080	0.352	0
F.A. (a).....	0.252	0.300	0.324	.....	0.419
C.A. (given) (b).....	0.400	0.400	0.400	0.400	0.400
Water (given) (w).....	0.200	0.200	0.200	0.200	0.200
Total.....	0.992	1.000	1.004	0.952	1.019
Proportion (abs. vol.).....	1:1.80:2.86	1:3.00:4.00	1:4.05:5.00	1:0.00:1.14	0:4.19:4.00
Proportion from 307a (abs. vol.).....	1:1.86:2.86	1:3.00:4.00	1:4.00:5.00	1:0.00:1.00	0:4.00:4.00

d. The batches are no longer of unit volume since only for the base batch does the sum of the absolute volumes now total unity. The batches are restored to the unit-volume basis by dividing the absolute volume of each constituent by the absolute volume of the batch. Thus for Batch 1 the cement in a unit volume of the concrete is $0.140 \div 0.992 = 0.141$. All ratios and the proportions remain unaltered in making this conversion.

BATCH QUANTITIES IN A UNIT VOLUME OF CONCRETE

Cem. (c).....	0.141	0.100	0.080	0.370	0
F.A. (a).....	0.254	0.300	0.323	.....	0.411
C.A. (b).....	0.403	0.400	0.398	0.420	0.393
Water (w).....	0.202	0.200	0.199	0.210	0.196
Total.....	1.000	1.000	1.000	1.000	1.000

e. Quantities for interchange by weight expressed as percentages of those for interchange by absolute volumes.

Cem. (c).....	100.7	100.0	100.0	92.5	
F.A. (a).....	97.8	100.0	100.8	.....	102.7
C.A. (b).....	100.8	100.0	99.6	104.8	98.3
Water (w).....	101.0	100.0	99.5	105.0	98.0

The differences in quantities are so slight that generally no cognizance need to be taken of them. The degree of approximation of the Lyse method itself probably exceeds by a sizable margin the

by weight are (see Table V) 0.16 and 0.18. These values are at the lower limit of the normal consistency range as tabulated in A.S.T.M. Designation C77-40, which gives the percentage of water for normal consistency as ranging from 15 to 30 per cent of the cement by weight. A normal-consistency mixture of neat cement without aggregate is just barely workable with vigorous thumbing. Obviously then, Batch 4 will be too dry for workability. If the cement stiffens the mixture to that extent, it stands to reason that for fine aggregate only (Batch 5) the 0.20 water requirement will be excessive.

h. Answer in the light of the results of your own tests.

308. a. Yes, approximately at least. It is possible to determine the relative water content that will give the desired workability (slump) for the neat cement. Unless the fine aggregate contains an unusual amount of fine material, the mixing water may tend to separate from the aggregate so that it will not be easy to determine just what water content for Batches 5 and 7 will produce the desired slump. If this difficulty is encountered, Batch 7 may be replaced by a relatively lean batch in which enough cement is present to prevent undue segregation. The "cement equivalent" for a given fine aggregate would not be of general application because of differences in grading and character of different aggregates. The more very fine material a fine aggregate contains, the more nearly will the equivalency approach unity.

b. The sum of the absolute volumes of cement and fine aggregate will not add up to a fixed amount for the different batches and the difference will

d. No. The practical application of the method simply involves adding or deducting 1.5 or 2 lb. of sand for every pound of cement added or

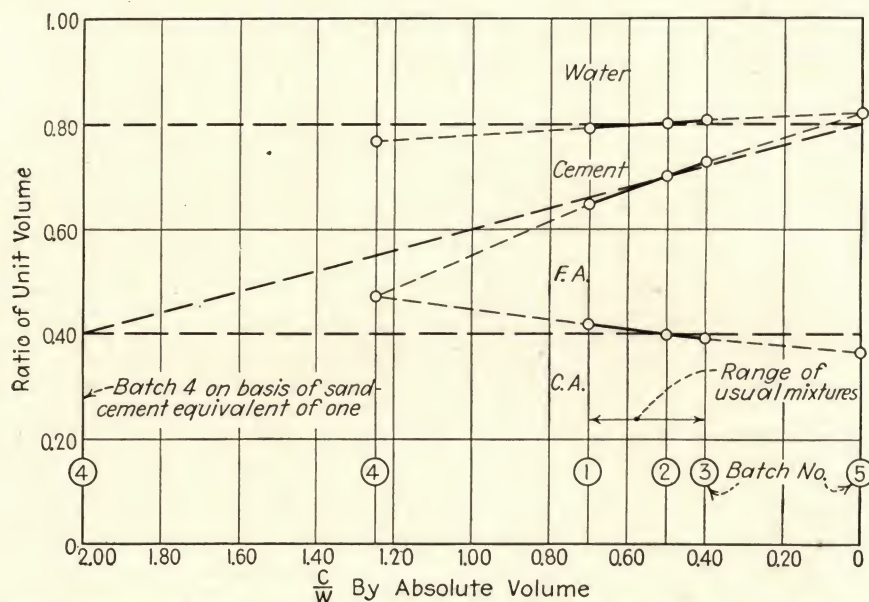


FIG. 34.—Effect of sand-cement interchange upon proportions for fine-aggregate-cement equivalent of 2.0, except for batch shown at left-hand margin. (Note very slight effect that the variation in the sand-cement equivalent has within the range of usual mixtures.)

slightly alter the relative quantities of water and coarse aggregate.

c. The results for F.A.-Cem. equivalent of 2.0 are shown in the following tabulations and on Fig. 34. (See answer to Question 307a for tabulated results for equivalent of 1.) The assumed equivalent of two is about right for a rather coarse sand deficient in fines and represents about the upper value for the sand-cement equivalent. Usual values may be expected to range between 1.5 and 2. As sand is decreased (and cement is increased), the coarse aggregate and water are increased correspondingly, although the relative amount of the increase in coarse aggregate and water is not great within the range of practicable mixtures.

deducted from the batch, as was done in the initial tabulation under part c. The reduction to the unit-volume basis is necessary only if an accurate calculation of yield is desired.

BATCH QUANTITIES IN A UNIT VOLUME OF CONCRETE

Cem. (c).....	0.146	0.100	0.078	0.294	0
F.A. (a).....	0.229	0.300	0.333	.....	0.455
C.A. (b).....	0.417	0.400	0.393	0.471	0.363
Water (w).....	0.208	0.200	0.196	0.235	0.182
Total.....	1.000	1.000	1.000	1.000	1.000

COMPARISON OF PROPORTIONS

F.A.-Cem. Equiv. = 1.0 1:1.86:2.86 1:3.00:4.00
 1:4.00:5.00 1:0.00:1.00 0:4.00:4.00
 F.A.-Cem. Equiv. = 2.0 1:1.57:2.86 1:3.00:4.00
 1:4.25:5.00 1:0.00:1.60 0:5.00:4.00

F.A.-CEM. EQUIVALENT = 2.0 BY ABS. VOL.

	Batch No. (Series I)				
	1	2	3	4	5
	(base)				
Design strength, p.s.i.	4900	3000	1700	.....	0
c/w abs. vol.	0.70	0.50	0.40	1.25	0
Cem. (given) (c).....	0.140	0.100	0.080	0.250	0
F.A. (a).....	0.220	0.300	0.340	.....	0.500
C.A. (given) (b).....	0.400	0.400	0.400	0.400	0.400
Water (given) (w).....	0.200	0.200	0.200	0.200	0.200
Total.....	0.960	1.000	1.020	0.850	1.100

309. a. According to the water-cement-ratio criterion, all mixtures which are workable should give equal strengths if similarly cured. Batch 1 should be harsh and unworkable, probably with some honeycombing. It does not, therefore, fall within the "law" and is not expected to equal the other batches in the strength developed.

b, c, d, e, f. Answer on the basis of the results secured.

310. a. All batches that are workable should have identical strengths.

b and c. Answer on basis of results secured.

311. *a* and *b*. Answer on basis of results secured.
- c*. No. The "dry at test" means a more or less uniform state of dryness throughout the specimen. Mere surface dryness has no significant influence upon strength. The gain in strength from drying out begins to become measurable after about a day in dry air. The rate of drying out to maximum increase in strength from drying varies with the size of specimen (its specific surface) and with the humidity of the air to which it is exposed; the higher the humidity and larger the specimen, the slower the gain in strength from drying out. Specimens 6 in. by 12 in. may be expected to attain maximum strength from drying out in from 2 to 3 weeks in a humidity range of 50 to 80 per cent (see *Concrete*, Vol. 49, No. 5, p. 4, May, 1941).
- d*. From 12 to 24 hr. is usually sufficient to insure virtual saturation which is the condition approached for the "wet-at-test" specimens.
- e*. Several days. Resumed-curing effects are rarely, if ever, discernible after only 2 or 3 days of re-immersion.
- f*. Figure 25 is for high-early-strength mixtures. These gain most of their strength at a very early age and subsequent environmental conditions have much less to do with the strengths developed than they do for specimens of normal portland cement.
312. *a*. They are to be kept continuously moist at a temperature between 65 and 70 F. and are to be moist at test (A.S.T.M. Designation C39-39).
- b*. In the saturated condition (*i.e.*, after 12 to 24 hr. of immersion). There are many possible degrees of dryness which will give varying strengths. Water is as wet one place as another and the state of virtual saturation can be attained for most mixtures within the designated period of soaking.⁷
- c*. They should be immersed for 12 to 24 hr. prior to test. The ends should be capped as outlined in the chapter on compressive testing. A correction factor will need to be applied to the results secured to compensate for the variable height-diameter ratio (see Chap. V).
- d*. They should be kept moist and should not be exposed to unusual temperatures. The period in transit should be as short as possible.

Chapter XII

(See p. 122 for questions.)

Experimental Aids in Stress Analysis

313. *a*. Until relatively recent times mathematics remained largely an abstract science applied extensively to astronomy, somewhat to physics and abstract mechanics, but almost not at all to the mechanics of materials. One primary reason was the lack of development of the practical testing techniques which demonstrated that

engineering materials have measurable properties and characteristics which can be related mathematically to their behavior in machines and structures.

- b*. Materials testing is the only means of investigating the quantitative response of materials to force systems under controlled measurable conditions. Only through the actual testing of materials can the underlying constants required for design be evaluated.
- c*. The limitations of both our testing techniques and our mathematical techniques are such that only the simpler cases of members and loadings can be "designed."
- d*. Because these types have proved satisfactory for long periods of service. They have been developed empirically and are relatively simple to fabricate but are sometimes complicated to analyze. In such cases evolution has dictated current practice. An evolved design has usually withstood the hazards of use, and this is the ultimate test of any design.
314. *a*. Structures which did not collapse were considered to be satisfactory, and each successive structure embodied only minor departures from similar existing structures. Failures halted venture-someness, just as they do today, and supplied valuable lessons on "how not to do it next time." The hesitancy to depart from prevailing conventional architectural styles also tended to stabilize types of construction. This conservatism may be but another manifestation of a fearsomeness to depart from what had proved to be safe practice.
- b*. Most laws were probably stumbled upon accidentally. The principles of the arch were doubtless evolved long after man recognized that holes through masonry walls do not necessarily bring collapse. Men used beams, in the form of logs and stones, long before they could be analyzed by a flexure formula.
315. *a*. No. The design may be highly uneconomical.
- b*. No. In many cases the cracks and visible signs of distress are results of unseen primary weakness or failure just as the visible signs of human illness rarely appear to be related to the basic germ or bacterial cause of the malady.
- c*. No. Other factors such as environment may have a marked effect upon the results. For example, a large concrete prototype will often be punished severely by the shrinkage and swelling which accompany temperature or moisture change, whereas the same two items might well be negligible in a small model. The boundaries of the small model are free to expand or contract, whereas an equivalent volume within the larger mass is restrained by the material surrounding it. Under these conditions the environmental factors are not the same for model and prototype.
316. *a*. The material of Chap. XII supplies supplementary or experimental aids to stress analysis

⁷ Occasionally there are mixtures which after drying out will, for no apparent reason, reabsorb very little water.

which can in many cases be used to simplify, clarify, or verify designs. Some of the methods are those of analogy.

- b. For the most part Chap. XII deals with members rather than materials. It is more intimately related to the testing or analysis of units of machines or structures than to the materials of which they are made.

317. a. (1) Elastic range:

Measurements of reaction, strain, or deflection are usually made on structures or models which are in the elastic range of stress, although measurements of reaction or strain are equally valid in the plastic range if appropriate methods are employed for evaluating the stress.

Plastic models (under some conditions).¹

Brittle-material models.

Photoelastic models.

Electrical analogy.

Membrane analogy.

Hydrodynamical analogy.

Slab analogy.

(2) Plastic range:

Sand-heap analogy.

Plastic models (under some conditions).¹

Measurement of reaction or strain (when material is in plastic range of stress).

- b. The membrane analogy, sand-heap analogy, and the photoelastic method are well adapted for use in demonstrations since they readily indicate the regions of stress concentration or the relative strengths of different shapes.

318. a. (1) Locations of stress concentration and the general distribution of stress are evident by the spacing and shapes of the visible bands. The quantitative determination of stress intensity is not evident, in general, from a simple inspection of the visible bands but requires careful measurement and analysis.

- (2) The regions of maximum shearing stress are readily evident as the sections at which the slope of the membrane is the greatest. The torque required to produce a given change in the angle of twist is proportional to the volume under the membrane.

- (3) The relative torque required to produce plastic action throughout the section is given by the volume of sand retained on the plate.

- b. When used under controlled conditions and with attention to certain limitations, all the methods will yield quantitative results.

319. a. The material must be transparent and optically sensitive. In general, it should be workable to the extent of being readily cut, drilled, and ground or polished. For most studies elastic action is desirable.² The material must have a capacity

¹ Devices such as the brittle paint and Lüders' lines methods are normally used to indicate the end of elastic action and the beginning of plastic action in the member being investigated.

² One of the methods of studying three-dimensional stress situations (see Reference 38, Art. 106) makes use of the controlled plastic action of the material. For other conditions elastic action is essential.

for being annealed to remove residual stresses induced in manufacture or by the shaping process.

- b. The membrane must be homogeneous and isotropic, be weightless, and have no resistance to bending.

- c. The material must be uniform and have a straight-line stress-strain diagram to the ultimate.

Obviously most of the limitations could be met fully only by ideal (and therefore fictitious) materials. For each use, however, materials are available which can be made to yield excellent results.

320. a. A model is a fabricated member or structure which may or may not resemble the prototype. It is expected to perform either like the prototype or analogously to it in certain comparable respects. A specimen is simply a unit of the material prepared for test to evaluate the strength and/or other physical properties of the material.

- b. Certainly in most cases; possibly in all.

321. a. (1) See References 3 to 14, inclusive.

- (2) See References 17 to 38, inclusive.

- b. (1) Wind-tunnel tests for airplane propellers and airfoils; tests of cars for wind resistance, gasoline consumption, tire wear, and friction on different road surfaces; performance tests on turbines, locomotives, and heating plants.

- (2) Hydraulic tests on models of spillways, as for Grand Coulee or for Shasta and Boulder (Hoover) Dams; tests on models of river channels many of which are conducted in such large river-hydraulics laboratories as those at the University of Minnesota and University of Iowa, also the National Hydraulic Laboratory at Vicksburg, Miss. and the model of the Cape Cod Canal at Massachusetts Institute of Technology. About 1921-1923, scale model tests were made at the University of Illinois on a several-hundred-foot length of air duct for the ventilation system of the Holland Vehicular Tunnel under the Hudson River in New York City. With the uses and limitations of model testing becoming ever better understood and structures of all kinds becoming more complicated, it is not surprising to find that a program of model testing is likely to represent one important aspect of any unusual engineering venture.

322. Larger, more important, and unprecedented structures are being built. Techniques for such investigations have been developed and improved greatly.

- 323. a. Usually it is, but actually the methods are far from exact. Within the limiting assumptions and conditions they give reasonably good results.**

- b. Yes.

324. During the first World War one of the urgent unsolved problems in design was that of evaluating the torsional strains and stresses in the noncircular cross sections of airplane propeller blades. The importance of the problem was not so much because of strength as it was the need for

knowing how a propeller blade could be expected to deform under conditions of use. St. Venant (1797-1886) had developed mathematical equations for finding the stress and torque in a twisted cylindrical body of any cross section and had reduced the problem to finding the solution of a certain differential equation. He was able to solve the differential equation for a few special cases such as the square or triangular cross section but was unable to evolve a general solution that could be made applicable to the majority of cases. Prandtl (1875-) showed in 1903 that the equation developed by St. Venant was of the same form as that expressing the displacement under uniform pressure of a homogeneous elastic membrane of a shape corresponding to the cross section of the member.

Major G. I. Taylor, an expert mathematician and qualified air pilot in the British Royal Air Force, was requested to investigate the torsion problem as applied to propeller blades.

Taylor recalled that he had seen an allusion to Prandtl's observation in a book, "The Mathematical Theory of Elasticity," by A. E. H. Love (1863-). From that as a starting point, and with the ingenious cooperation of A. A.

Griffith, he devised apparatus whereby the theory of Prandtl could be made to yield results of great practical importance. The first step by Taylor and Griffith was the recognition that a soap film is virtually a perfect elastic membrane which meets the necessary requirements. An excellent description of the work of Taylor and Griffith is given in the *Engineer* (London), pp. 536, 543-546, 1917.

325. There were violations. While the rubber itself was less homogeneous, isotropic, and elastic than a soap film and the plaster was not a perfect fluid, the major violation was in the variable height of the fluid plaster mixture which made the pressure greatest in the regions of maximum distension or bulging. The shape of the bubble resulting from the unequal pressure would vary somewhat from that required, and there would be corresponding changes in surface slopes and volumes. The plaster was 3 or 4 in. in depth, and the maximum distensions were from about $\frac{1}{4}$ to $\frac{3}{4}$ in. For qualitative use the errors are probably almost, if not entirely, negligible, but as a basis for accurate quantitative evaluations the errors would probably be objectionably large in comparison with the results attainable by the best of current techniques in the use of soap films.

APPENDIX B

Laboratory Organization

1. The Squad.—The students in a section will be grouped in squads of from two to four men for each problem. The squad will function as a unit, and each man will be assigned to one of the following positions: recorder, *r*; operator, *p*; observer, *b*; or computer, *c*. As far as practicable during the term a man will serve successively in different capacities. The assignment of problems will be made early in the term, and each student is expected to come to each laboratory period with definite plans for the work to be done. When there are fewer than four men in a squad, the duties outlined will be appropriately combined. The recorder may, for example, assume the duties allocated to the observer.

2. Duties of Recorder.—The recorder is the leader of the squad, and is responsible for the performance of the assigned problem in an orderly manner. He should give preliminary thought to the duties of the other members of the squad in order that the work may proceed properly and without delay. While each member of the squad will be held responsible for proper preparation of the assignment and for the performance of his duties in the laboratory, the responsibility for the coordination and general execution of the problem rests upon the recorder. He should, therefore, consult the instructor immediately if delays occur or if there is doubt regarding method of procedure.

The recorder will enter all data on a suitably ruled sheet or form, making one carbon copy for each man in the squad. Before any test data are taken, he should record the incidental information, such as squad personnel, date, title of problem, and an itemized list of the equipment. He should also secure the instructor's approval of the column headings and of the laboratory setup before testing is begun. *Only original observations are to be recorded as observed data.* Calculations made during the progress of the test will be entered in separate columns under the heading of results or calculated data. *Under no circumstances are observed data to be recorded elsewhere with the intent of transferring them later to the log sheet.* When all the observed data have been recorded and before removing carbons, the recorder will submit the log sheet to the instructor for approval.

3. Duties of Operator.—The operator is responsible for the care and proper functioning of all equipment except the measuring devices used by the observer. Before any data are taken, he should familiarize himself thoroughly, under the direction of the instructor, with the operation of the equipment in order to avoid possible difficulties during the test. He should report any broken or damaged equipment to the instructor immediately. He should clean up around the machine when the testing is completed and see that all equipment is left in the proper condition. He is also responsible for locking or checking in the tool kit for the squad.

4. Duties of Observer.—The observer will manipulate and be responsible for the measuring apparatus. He will

take the necessary readings and will be held accountable for their accuracy.

5. Duties of Computer.—The computer is responsible for whatever preliminary calculations may be necessary. He will determine the probable range of values to be measured and select suitable increments or observational intervals. These are to be checked by the instructor before the test is started. During the progress of the problem, the computer will assist in taking readings, if necessary, and will cooperate with the recorder in the calculation of results.

The Report

6. Preparation and Arrangement.—A report on each assigned problem is to be turned in by each man. The report sheets shall be arranged in the following order and shall be bound in a manila folder:

- a. Graph sheet.
- b. Data sheet.
- c. Sample calculations.
- d. Discussion.
- e. Log sheet (the carbon copy of original data).

7. Graph Sheet.—The following specifications apply to the graph and graph sheet:

- a. *Paper.*—The graph shall be drawn neatly on plotting paper.
- b. *Margin.*—The wide binding margin shall be on the right-hand side of the page.
- c. *Binding.*—The sheet shall be bound with two clips to the inside of the *top* cover of the folder so that it will appear as the left-hand page when the folder is opened.
- d. *Axes.*—The outside ruled lines of the paper shall be taken as the coordinate axes, except when this is incompatible with the data or when there are specific instructions to the contrary.
- e. *Label Axes.*—Each axis shall be labeled outside the ruled lines, the units being designated.
- f. *Choice of Scale.*—Scales selected shall be such that the ruled lines will be of assistance in reading the values corresponding to random points on the curve.
- g. *Designation of Scale.*—Numerical values of the coordinates shall be placed at 1-in. intervals along the axes (or at 2 cm. if a metric scale is used).
- h. *Plot all Values.*—All observed values shall be plotted.
- i. *Symbols.*—Different symbols shall be used for points in different series of data. Permissible symbols in the order of their suitability are \odot , $+$, \triangle , \square , \bullet , \blacktriangle , \blacksquare , \diamond , \blacklozenge , \times , $*$.
- j. *Smooth Curve.*—A smooth curve shall be drawn to represent the average of the plotted points, except when the function is discontinuous or when there seems to be a lack of definite relationship between plotted values. In this case, a point-to-point curve or series of straight lines may be preferable.
- k. *Discontinue the Curve.*—The curve shall be discontinued at its intersection with a symbol indicating a plotted point.

l. Title.—The graph sheet shall carry the problem number and a descriptive title in a prominent place within the border.

m. Supplementary Information.—Additional information, such as (1) the name of the student, (2) date, and (3) section number shall appear on the graph sheet.

n. Legend.—A legend, or key to all symbols, shall be given if more than one symbol or type of line is used.

o. Equation.—When the equation for a curve is known, it shall be written along the curve.

p. Construction Lines.—Show all construction lines used in attaining final values.

8. Data Sheet.—The following specifications apply to the data sheet:

a. Paper.—The data shall be tabulated on a suitably arranged sheet.

b. General Information.—The general information, including a list of the apparatus used, shall appear at the top of the sheet.

c. Original Data.—The numerical data shall include the original measurements as given on the log sheet and all reduced data such as those from which graphs are plotted.

d. Separate the Computed Data.—A line shall be drawn or a blank space left between the data which were observed and those which were computed.

e. Significant Figures.—Computed data shall carry not more than the number of significant figures consistent with the observed data and any numerical constants which were used. A slide rule will provide sufficient accuracy for most calculations (see Art. 22).

f. Decimal Point.—All data in a given column shall be carried to the same number of decimal points unless there is a discontinuity due to changes in method or precision of observation.

g. Cipher to Precede Decimal.—A cipher shall precede the decimal point for all numbers less than unity except that omission is permissible if the column is too narrow to accommodate the data otherwise.

h. Additional Information.—Any available supplementary information which would be of value in interpreting the results shall be included.

i. List Results.—Such results as numerical values for the properties of the material or equations to be determined shall be tabulated or recorded in an orderly manner on the data sheet.

j. Verify Results.—Whenever possible, results shall be compared with values from a textbook or other authority, definite page references being given in all such cases.

9. Sample Calculations.—The sample calculations shall consist of one line or set of representative data carried through all the calculations involved in working from the observed quantities to the results.

10. Discussion.—Discussion shall be included only when specified or when the results might be misinterpreted without it. It should include a brief statement of factors which were unusual and which may have influenced the results of the test but which are not fully apparent from the data sheet. Any peculiarities shown by the graph or data should be mentioned and explained if possible. Suggestions should be given on how to avoid discrepancies and peculiarities

which are believed to be caused by errors or unsatisfactory manipulation. A description of the routine aspects of the test is not wanted.

11. Log Sheet.—The carbon copy of the laboratory log sheet is to be bound in the report to facilitate reference to the original record in case of doubt.

Conduct of the Course

12. Supplementary Questions.—At the ends of chapters and following problem instructions are groups of questions which are intended

a. To forestall possible difficulties or misunderstandings by assisting the student to think his way progressively through problems which may arise.

b. To extend the scope of material introduced and to encourage resourcefulness by pointing out other applications and adaptations and calling attention to related matter.

c. To test the student's understanding of the problem and his appreciation of the significance of the various operations performed and results secured. Written answers to these questions as part of the report are not desired, but many of the questions are representative of what may be asked in the daily quiz or examination work of the course. A portion of the oral discussion of the problem may well be devoted to selected Supplementary Questions.

13. Final Examination.—As indicated previously there will be a final examination in which a satisfactory mastery of the course content must be demonstrated before credit can be allotted. The final grade in the course will take account of the quality of each of the several aspects of the work.

14. Regulations Relative to Attendance.—Since satisfactory completion of all assigned problems is prerequisite to credit in the course, regularity of attendance is essential. In case a period is missed, regardless of the reason therefor, the student should consult his instructor at the earliest possible date in order to determine how the missed work can best be made up. Make-up work will carry credit varying from zero to a maximum of one-half except for cases in which the absence was entirely and unquestionably valid.

15. Responsibility for Equipment.—Each squad will be assigned a tool kit for the term. As the same kit will be used by squads meeting at other periods, the contents should be checked at the beginning of each laboratory meeting, and any missing or damaged equipment reported to the instructor at once. Responsibility for the kit and other equipment rests with the squad as a unit. Members of a squad may reapportion an assessment for damaged or missing equipment among themselves if they do not consider that all members were equally responsible, but the entire squad is liable until full settlement has been made. With the exercise of reasonable care, charges for either loss or damage are rare.

It is important that all equipment be left alone until definitely assigned for use during the period specifically designated. Unauthorized handling sometimes results in serious damage to equipment or to research or other work in progress. Heedlessness on this point cannot be tolerated and may necessitate the imposition of a penalty.

APPENDIX C

TABLE VII.—AVERAGE VALUES OF PROPERTIES FOR SOME ENGINEERING MATERIALS

Material	Elastic strength					Ultimate strength,† p.s.i.	Mod- ulus of tough- ness,‡ in.-lb. per cu. in.	Mod- ulus of resili- ence,‡ in.-lb. per cu. in.	Modulus of elas- ticity, p.s.i.	Ulti- mate unit strain in 2 in.	Brinell hard- ness num- ber§	Endur- ance limit,|| p.s.i.	Wt. per cu. ft., lb.
	Type of stress	Propor- tional limit, p.s.i.	John- son's appar- ent elastic limit, p.s.i.	Yield* strength, p.s.i.	Yield point, p.s.i.								
Nickel-chrome steel S.A.E. 3130	Tension	215 000	.....	.....	.....	245 000	22 000	770	30 000 000	0.10	490	.....	490
High carbon steel S.A.E. 1095 (hot-rolled)	Tension	75 000	76 900	78 000	.....	120 000	5 000	93.7	30 000 000	0.08	265	60 000	490
Intermediate steel	Tension	42 000	43 000	47 000	48 000	75 000	16 000	29.4	30 000 000	0.25	150	34 000	490
Structural steel	Tension	36 000	37 000	42 000	42 000	60 000	16 000	21.6	30 000 000	0.30	120	30 000	490
Structural steel	Torsion	20 000	21 000	24 000	24 000	60 000	20 000	.....	12 000 000	.....	120	.....	490
Wrought iron	Tension	31 000	31 500	32 000	32 000	50 000	12 500	19.2	25 000 000	0.35	100	25 000	490
Gray cast iron	Tension	6 000	.....	.....	.....	20 000	80	1.2	15 000 000	0.005	160	.....	450
Gray cast iron	Flexure	10 000	.....	.....	.....	50 000†	.....	.....	15 000 000	.....	160	10 000	450
Duralumin 17S-T	Tension	27 000	28 000	37 000	.....	60 000	11 000	36.4	10 000 000	0.22	100	15 000	175
Red oak¶ (green)	Flexure	4 100	.....	.....	.....	8 000†	34	0.7	1 350 000	.....	1060§	||	63
Red oak¶ (kiln dry)	Flexure	8 500	.....	.....	.....	14 000†	33	2.3	1 820 000	.....	1580§	||	44
Red oak¶ (kiln dry)	Compr.	4 600	.....	.....	.....	6 800	24	.....	.....	0.006	1580§	.....	44
Douglas fir¶ (green)	Flexure	4 800	.....	.....	.....	7 600†	19	0.9	1 500 000	.....	510§	||	38
Douglas fir¶ (dry)	Flexure	8 100	.....	.....	.....	11 700†	23	2.0	1 900 000	.....	760§	||	34
Douglas fir¶ (dry)	Compr.	6 500	.....	.....	.....	7 400†	34	.....	.....	0.008	760§	.....	34
White pine¶ (green)	Flexure	3 100	.....	.....	.....	5 000†	11	0.5	1 000 000	.....	310§	||	36
White pine¶ (dry)	Flexure	6 000	.....	.....	.....	9 000†	10	1.6	1 300 000	.....	500§	||	25
White pine¶ (dry)	Compr.	3 700	.....	.....	.....	5 000	19	.....	.....	0.005	500§	.....	25
Concrete (medium)**	Compr.	1 200	1 600	2 000	.....	2 500	4	0.2	3 000 000	0.002	.....	1 200	150
Concrete (strong)**	Compr.	3 500	4 000	5 000	.....	6 000	8	1.2	5 000 000	0.002	.....	3 000	150

* Yield strengths are for offsets recommended in Chap. II.

† All ultimate flexural strengths are "moduli of rupture."

‡ Values for flexural resilience and toughness of timber are from areas under load-deflection curves of the standard flexural specimens and represent the average work per unit volume required in stressing the material to the proportional limit or to failure. They are not equal to the modulus of resilience or modulus of toughness for the materials because of the variation in stress throughout a flexural member.

§ Hardness of timber is the load required to embed a 0.444-in. ball to one-half of its diameter in the timber. Values given are for the hardness of an end section.

|| Endurance limit of timber in flexure may be taken at about one-third the flexural modulus of rupture.

¶ Ratio of properties of kiln-dry timber to those for timber which is green or moist are approximately as follows: 1.80 for elastic strength (flexure or compression parallel to grain); 1.60 for modulus of rupture; 2.00 for ultimate compressive strength; 1.30 for modulus of elasticity (stiffness); 2.50 for flexural resilience; 1.10 for modulus of toughness. All results are for small clear specimens. Timber in structural sizes with ordinary defects may be expected to be at least one-third weaker. Timber designated by the same name in different sections of the country may differ materially in the values for most properties. These data are for some of the widely used species and are approximately those reported by the Forest Products Laboratory, L. J. Markwardt and T. R. C. Wilson, Strength and Related Properties of Woods Grown in the United States, *Tech. Bull.* 479, U. S. Dept. Agr., Washington, D. C., 1935.

** The ultimate compressive strength of concrete may vary from 2000 to nearly 10,000 p.s.i., depending upon proportions, curing, etc.

APPENDIX D

TYPICAL FINAL EXAMINATIONS . . . . .	163

FINAL EXAMINATION (124018)

T. & A. M. 327, 337¹

Materials Laboratory

Name _____ Date _____

Show all necessary construction directly on this sheet, and hand in with bluebook. Place all calculations, including scratchwork, and all results in bluebook.

1. Data for the plotted points shown in Fig. 35 were obtained during a compressive test of a 2.00-in. diameter portland-cement-mortar specimen. Determine values

- a. For Johnson's apparent elastic limit.
- b. For the modulus of elasticity.
- c. For the yield strength corresponding to an offset of 0.02 per cent.
- d. For the modulus of resilience.
- e. For the total energy absorbed in the 3-in. gage length of the specimen when stressed to the ultimate.

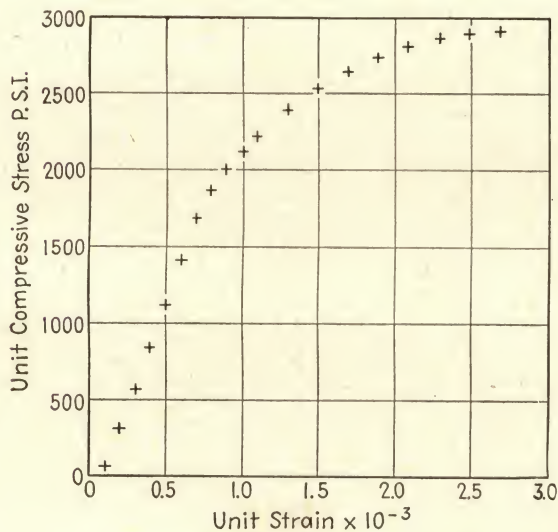


FIG. 35.

2. a. Name three methods which may be used to determine the yield point during a commercial tensile test of steel.

b. Determine the increments of dial divisions to insure 10 readings within the elastic range during a torsional test of a 1.00-in. diameter steel bar, the estimated proportional limit of which is 24,000 p.s.i. The dial is placed 2.00 in. from the center of the bar and has a least count of 0.001 in. The gage length is 8.00 in.

c. In the laboratory experiment Precise Tension Test of Steel, why were readings taken at equal increments of dial divisions rather than at equal increments of load?

¹ At Iowa State College T. & A. M. 327 is a one-credit course for one quarter, while T. & A. M. 337 is a two-credit course for one quarter. (See Foreword to Instructors for details.)

d. For the material of a helical spring the modulus of rigidity can be expressed as a function of the load-deflection diagram. Indicate the nature of this relationship.

e. Explain briefly how the modulus of elasticity of a material may be determined from a column test. Would the value determined in the laboratory have been larger or smaller if the knife-edge or other pinned or pivoted column-end fixtures had not been used?

f. What is meant by "stress-concentration factor"?

g. Name two properties which a satisfactory material for photoelastic stress analysis must possess.

Question 3 for Students in 337 Only

3. a. What is a specification?

b. Differentiate briefly between a specification and a contract.

c. Describe two methods by which tensile tests may be made on the material of steel pipes.

d. Name two devices with which testing machines may be calibrated.

e. Does the multiplication ratio of a lever-type testing machine vary with changes in temperature? Explain.

f. In the experiment in which strains in a steel beam were measured directly with a Whittemore or a Berry strain gage, why was two-point symmetrical loading used?

g. Why should the scleroscope reading be taken at the first rebound of the plunger from a given position on the specimen?

h. Name one advantage which the hydraulic-type testing machine has over the gear-type testing machine. Name one advantage of the gear type over the hydraulic type.

FINAL EXAMINATION (123816)

T. & A. M. 327

Materials Laboratory

Make no marks on this sheet. All scratchwork to be in the bluebooks

1. The following data were obtained during a tensile test of a magnesium alloy rod (Fig. 36 indicates a sketch of the extensometer used):

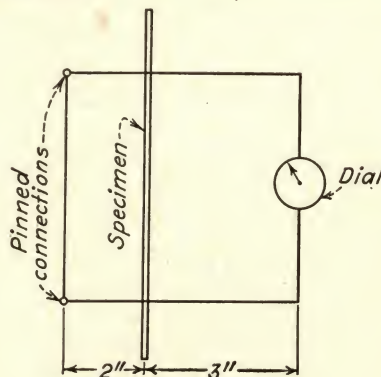


FIG. 36.

No.	Dial reading, divisions	Load, lb.	Average diameter = 0.874 in. Gage length = 4.00 in. Least count of dial = 0.001 in.
0	300	0	
1	295	1 200	
2	290	1 920	
3	285	3 900	
4	280	5 630	
5	275	7 510	
6	270	9 600	
7	265	11 400	
8	260	13 200	
9	255	14 400	
10	250	15 230	
11	240	16 300	
12	230	16 790	
13	210	17 600	
14	190	18 100	
15	170	18 600 (load removed)	

Determine if possible (otherwise mark "none," or "data not secured") the following:

- Proportional limit.
- Johnson's apparent elastic limit.
- Yield point.
- Yield strength for an offset of 0.2 per cent.
- Percentage elongation.
- Modulus of resilience.
- Toughness.
- The total work absorbed within the 4-in. gage length while elongating 0.040 in.
- Poisson's ratio.
- Modulus of elasticity.

2. Complete the following statements. Only the answers need be written in the bluebooks.

- The highest speed of a testing machine should be used solely in _____.
- Two mechanisms used with a strainometer to measure relative movements are dial indicators and _____.
- The percentage reduction of area of a metal bar tested to rupture is a measure of the _____ of the material.
- The upper limit of the ratio of height to diameter for a compressive test specimen which may be expected to give a reasonably correct indication of the compressive strength of the material is approximately _____.
- A troptometer is used to measure _____.
- The apparent yield point as determined during the torsional test for steel is _____ (higher or lower?) than the actual yield point of the material.
- The following property or properties of the material were evaluated in the test of a helical spring: _____.

h. In a testing machine it is _____ (possible or impossible?) to test a slender column to the ultimate without producing structural damage.

i. Three analogies that may be used in stress determinations are _____, _____ and _____.

j. One example of a situation in which a supplementary method of stress evaluation, i.e., the determination by means other than mathematical analysis, is necessary is _____.

k. For the case mentioned in part j the elementary mathematical analysis is unsatisfactory because _____.

l. The stresses could be evaluated in the preceding situation by _____.

FINAL EXAMINATION (6396)

T. & A. M. 327, 337

Materials Laboratory

Name _____ Date _____

1-credit students answer questions 1 and 2.

2-credit students answer questions 1, 2, and 3.

Show all necessary construction on this sheet and hand in with bluebook. Place all calculations, including scratchwork, and all results in bluebook.

1. Data for the plotted points shown in Fig. 37 were obtained during a compressive test of a 6.00-in. diameter concrete cylinder. Determine values

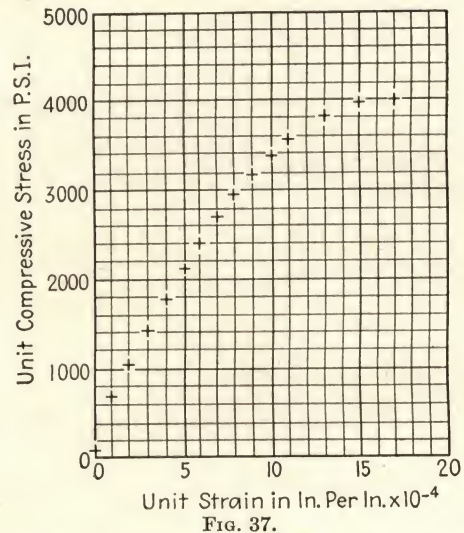


FIG. 37.

- For the modulus of elasticity of the material.
- For the yield strength corresponding to an offset of 0.02 per cent.
- For two other indexes of the elastic strength.
- For the modulus of resilience of the material.
- For the total energy absorbed within the 8-in. gage length at rupture.

2. a. Why is the term *apparent yield point* used in connection with torsion tests instead of the term *yield point*?

b. On the basis of the following values, determine the approximate dial movement up to the proportional limit, during a torsional test of a round bar: gage length = 10.00 in., distance from surface of bar to center of dial plunger = 2.00 in., diameter of bar = 1.00 in., least count of dial = 0.001 in., proportional limit = 20,000 p.s.i., and $E_s = 10 \times 10^6$ p.s.i.

c. What information may be obtained by use of the soap-film analogy?

d. What property or properties must the material of every photoelastic model for stress analysis possess?

e. Name three methods which may be used for determining the tensile yield point of structural steel.

1. Data for the plotted points shown in Fig. 38 were secured during a tensile test of an alloy steel. Determine values

a. For the elasticity.

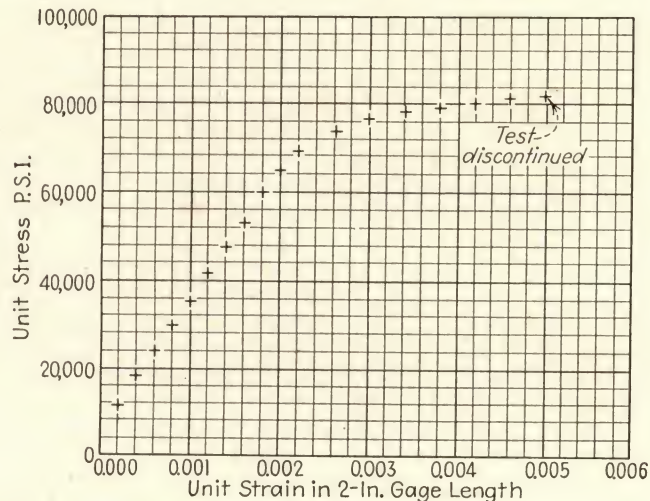


FIG. 38.

f. What property or properties of the material were evaluated in the problem on the elastic curve of a beam?

g. The modulus of rigidity of the material in a helical spring is proportional to _____ of the load-deflection diagram.

h. If there had been appreciable frictional restraint in the column-end-fixtures, how would the value obtained for the modulus of elasticity have been affected?

Question 3 for 2-hr. Credit Students Only

3. a. A.S.T.M. specifications for compressive tests of brick specify that the faces to be capped shall first be shellacked. Why?

b. Define error as applied to the calibration of a testing machine.

c. Does the "multiplication ratio" of a lever-type testing machine vary with changes in temperature? Explain.

d. In the test of the timber beam (simply supported with the load at the center) what property was determined from the test on the short span that could not be evaluated from the test on the long span?

e. What is the approximate relationship between the tensile strength of a steel and its Brinell hardness number?

f. In the experiment using the Whittemore or the Berry strain gage, why were readings taken on the standard bar?

g and h. If the weight of the poise of a lever-type testing machine is 20 lb. and the capacity of the machine is 60,000 lb., approximately how far is the platen of the machine depressed for a 1-in. rise of the free end of the scale beam?

FINAL EXAMINATION (34113)

T. & A. M. 327, 337 Materials Laboratory
Name _____ Date _____

Students in T. & A. M. 327 answer questions 1 and 2

Students in T. & A. M. 337 answer questions 1, 2, and 3

Show all necessary construction on this sheet and hand in with bluebook.
Place all calculations, including scratchwork, and all results in bluebook.

b. For the modulus of elasticity.

c. For the modulus of resilience.

d and e. For two properties which are indexes of the elastic strength.

2. a. State which of the following properties will be in error if the multiplication ratio of the strainometer is determined incorrectly: Proportional limit, elasticity, yield strength, yield point, modulus of elasticity, modulus of resilience.

b. Explain why the percentage elongation of a structural steel bar in 2 in. exceeds that in 8 in.

c. What is the function of a spherical bearing block?

d. State how the modulus of a spring for three turns compares with that for one turn, and indicate which modulus was evaluated for the spring you tested.

e. Determine the increments of dial divisions to insure 10 readings in the proportional range during a torsional test of a 1.00-in. diameter steel rod, the estimated proportional limit of which is 24,000 p.s.i. The dial is placed 2.00 in. from the center of the bar and has a least count of 0.001 in. The gage length is 15 in.

f. Explain briefly how the modulus of elasticity of a material may be determined from a column test. State any limitations which may apply to the use of the method.

g. Explain a method for determining the stress-concentration factor for a point at the peak of a notch in a beam.

h. In the soap-film analogy the slope of the film surface at a point is proportional to _____ and the volume under the film is proportional to _____.

Question 3 for Students in 337 Only

3. a. Who was Charles B. Dudley?

b. Will a uniform change in temperature alter the multiplication ratio of a lever-type testing machine? Explain.

c. Is the sluggishness of a testing machine proportional to the load? What are causes of sluggishness?

d. Why should the surface of a brick specimen be shel-lacked before capping?

e. Compute the stress constant for a 6-in. strain gage for which one dial division equals 0.0001 in. total movement of the movable leg. The gage is to be used for stress determinations on concrete having a modulus of elasticity of 3,000,000 p.s.i.

f. Why should the scleroscope reading be taken at the first rebound of the plunger from a given position on the specimen?

g. Describe specimens suitable for use in tensile tests of the material (a) in a small pipe, (b) in a large pipe.

FINAL EXAMINATION (33819)

T. & A. M. 337

Materials Laboratory

Name _____ Date _____

Make no marks on this sheet. All scratchwork to be in the bluebooks.

1. The following data were obtained during a torsional test of an alloy rod: Diameter of rod = 1.000 in.; gage length = 10.00 in.; radius of troptometer arm = 2.00 in.; least count of dial = 0.001 in.

Torque, in.-lb.	Dial reading, divisions	Torque, in.-lb.	Dial reading, divisions
0	0	4030	110
800	10	4340	120
1200	20	4550	130
1530	30	4770	140
1840	40	4930	150
2150	50	5200	170
2470	60	5420	190
2790	70	5590	210
3100	80	5730	230
3410	90	5860	250
3720	100	6000	270

Determine values

a. For modulus of rigidity.

b. For apparent yield strength corresponding to an offset of 0.2 per cent.

c and d. For two other measures of the elastic strength in torsion.

e. For the total energy absorbed in the gage length in applying the 6000 in.-lb. of torque.

2. Complete the following statements. Only the answers need be written in the bluebooks.

a. An extensometer is used in a _____ (what kind of?) test.

b. Three methods for evaluating the yield point from a specimen of hot-rolled structural steel are _____

c. The two essential parts of a testing machine are _____

d. To evaluate the toughness of a material the test must be carried to _____

e. The function of the column ends used in the column test was to _____

f. The multiplication ratio of a compressometer is _____

g. The spherical bearing block is used to adjust for _____

h. The modulus of rigidity of the material in a helical spring is proportional to _____ of the load-deflection diagram.

i. Two methods by which stresses in structures may be evaluated from observations on the structures are _____

j. In the soap-film analogy the slopes of the bubble surfaces are proportional to _____

3. a. What maximum permissible error in a testing machine does A.S.T.M. Designation E4-36 permit?

b. In the calibration of a compressometer having a gage length of 6 in., it was found that a movement of 100 divisions on the ten-thousandth dial of the compressometer corresponded to a movement of 0.0025 in. of the calibrator sleeve. Determine (1) the multiplication ratio of the compressometer and (2) the unit deformation corresponding to a movement of one dial division on the compressometer.

c. What property may be evaluated from a flexural test of a timber beam (simply supported with a concentrated load at the center) on a short span that cannot be evaluated from a test on a long span?

d. Between what variables does Dohmer's formula express a relationship?

e. Give the location, and state the capacity of one of the large testing machines in the United States.

FINAL EXAMINATION (6379)

T. & A. M. 337

Materials Laboratory

Name _____ Date _____

Make no marks on this sheet. All scratchwork to be in the bluebooks.

1. From the following data obtained during a compressive test of a square concrete prism, evaluate

a. The modulus of elasticity of the material.

b. The toughness of the material.

c and d. Two properties which are measures of the elastic strength of the material.

e. The maximum energy which could be absorbed in the gage length without stressing the material beyond the proportional limit.

Cross section of prism = 4.00 in. by 4.00 in. Multiplication ratio of compressometer = 2.00. Gage length = 5.00 in. Least count of compressometer dial = 0.0001 in.

Load, lb.	Dial reading, divisions	Load, lb.	Dial reading, divisions
0	100	30 000	135
3 000	101	35 000	140
6 000	103	40 000	148
9 000	107	45 000	157
12 000	111	50 000	166
15 000	115	55 000	176
18 000	118	60 000	187
21 000	123	65 000	198
24 000	127	70 000	218
27 000	131	72 500	244

2. a. Outline briefly a procedure for evaluating the modulus of resilience in torsion for steel from data taken on a helical tension spring.

b. Why are the knife-edges used in the column-end fixtures?

c. What experimental test method would be most suitable for investigating torsional stresses in a shaft having a uniform T-shaped cross section? Show on a sketch where the high and low stresses would be expected to occur.

d. Is modulus of elasticity a measure of strength, stiffness, elasticity, or capacity for absorption of recoverable energy?

3. a. A 10-in. strain gage with a ten-thousandths dial is used to measure strains in structural-steel concrete reinforcing bars. What is the stress increment corresponding to a change in dial reading of 90 divisions? Is the stress corresponding to 180 divisions twice that for 90 divisions? Explain your answer.

b. Describe, with the aid of a sketch, a specimen suitable for a tension test of a brittle material.

c. Define "error" as applied to the calibration of a testing machine.

d. What limits of allowable error in a testing machine are prescribed by the A.S.T.M.?

FINAL EXAMINATION (123916)

T. & A. M. 327, 337

Materials Laboratory

Name _____ Date _____

Students in T. & A. M. 327 answer questions 1 and 2.

Students in T. & A. M. 337 answer questions 1, 2, and 3.

Draw all necessary construction lines directly on this sheet and hand in with bluebook. Place all calculations, discussion, and results in the bluebook.

1. Data for the plotted points shown in Fig. 39 were secured during a torsional test of an alloy rod,

diameter = 0.500 in., gage length = 8.00 in.

Determine values

a. For the apparent yield strength for an offset of 0.2 per cent.

b and c. For two other indexes of the elastic strength.

d. For the modulus of rigidity of the material.

e. For the total amount of energy absorbed within the gage length in stressing the material to 29,400 p.s.i.

f. For the average amount of energy absorbed per unit of volume in stressing the material to 29,400 p.s.i.

2. a. (1) Name three methods which may be used to evaluate the yield point during a commercial tensile test of steel.

(2) For the laboratory experiment Precise Tension Test of Steel why were readings based on increments of dial divisions instead of on increments of load?

- b. (1) Name the two essential parts of a testing machine.
(2) Why was a spherical bearing block used in the compressive test?

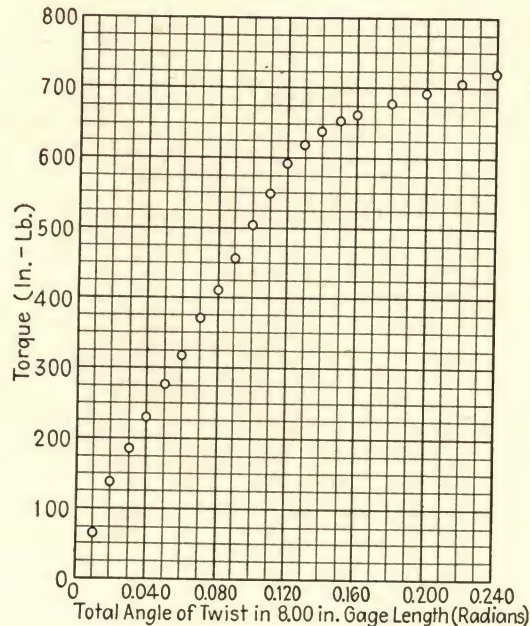


FIG. 39.

c. (1) Name three laboratory tests that are used to test, or to check on, the ductility of metals.

(2) In the problem on the elastic curve of a beam, where, along the beam, did the maximum moment occur? The maximum deflection?

d. If there had been appreciable frictional restraint in the column-end fixtures, how would the value determined for the modulus of elasticity have been affected?

e. (1) A material to be satisfactory for a brittle material model must have a straight-line stress-strain diagram to the ultimate. Name one such material.

(2) Name an analogy which may be used to study torsional stresses when the stresses are below the proportional limit. When they are above.

3. a. The strain gage has several important advantages over other types of strainometers. State three of them.

b. Define and distinguish clearly between error and correction as applied to a testing machine.

c. Explain the purpose of testing the timber beam on the short span after it had already been tested on the long span.

d. Give the approximate recorded date for the development of the first practical testing machines.

e. Name three kinds of tests for brick as given in A.S.T.M. Designation C67-41.

SUBJECT INDEX¹

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¹ Reference to questions, indicated as Q.(), will best be made by first contacting the answer or discussion in Appendix A where all the treatments are in sequence and page references to statements of questions have been inserted at the head of each group of questions. Occasionally the statement of the question may be surmised from the answer or discussion, but in general the original wording of the question should be checked. Answers are not intended to be exhaustive or complete, but they will usually supply enough of a clue to enable an interested person to contact source material. The question-answer feature has been introduced for suggestiveness rather than inclusiveness.

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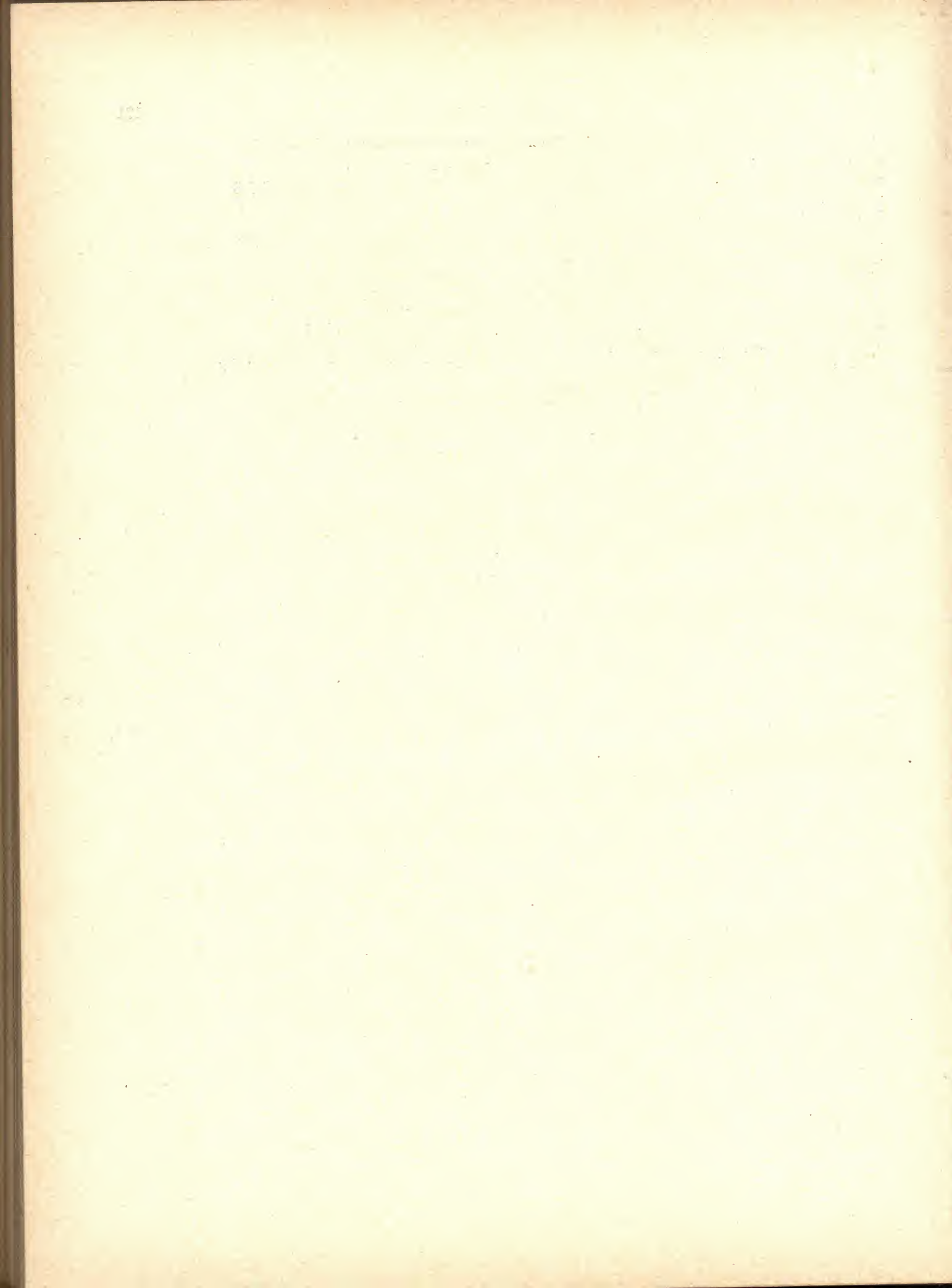
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